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INVESTIGATION OF A PERSONNEL RESTRAINT SYSTEM FOR ADVANCED MANNED FLIGHT VEHICLES

TECHNICAL DOCUMENTARY REPORT NO. AMRL-TDR-62-128

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Life Support Systems Laboratory
6570th Aerospace Medical Research Laboratories
Aerospace Medical Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

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Contract Monitor: Mr. James W. Brinkley
Project No. 6301, Task No. 630102

2308

[Prepared under Contract No. AF33(600)41418
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FOREWORD

This study was initiated by the Protective Equipment Section, Protection Branch, Life Support Systems Laboratory, 6570th Aerospace Medical Research Laboratories at Wright Patterson Air Force Base, Ohio. The research was conducted by the Astronautics Division of the Chance Vought Corp, Dallas, Texas, under Contract No. AF33(600)-41418. Mr. Howard E. Freeman, Design Engineer, was the principal investigator for the Chance Vought Corporation. Mr. James W. Brinkley, of the Protective Equipment Section, Protection Branch, Life Support Systems Laboratory, was the contract monitor for the Aerospace Medical Research Laboratories. The work was performed in support of Project 6301 "Aerospace Systems Personnel Protection" and Task No. 630102 "Personnel Protection in Aerospace Systems." The research sponsored by this contract was started in May 1960 and completed in February 1962.

Acknowledgement is sincerely given to the following members of the Astronautics Division of Chance Vought Corp who contributed to this work: Messrs. R. McKinney, C. Adams, R. J. Garnett, A. B. Thompson, B. P. Clark, R. M. Johnson, V. Igou and F. Thomas.

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Animal experimentation reported herein was performed in accordance with the "Principles of Laboratory Animal Care" established by the Institute of Laboratory Animal Resources, National Academy of Sciences.

ABSTRACT

To develop new concepts for personnel restraint, the following studies were conducted. Characteristic accelerations were defined for advanced manned flight systems. Accelerations of 8 to 12 G which are associated with ballistic reentry, produce the most severe physiological stress. Landing impact, generating low-total-energy accelerations of 60 to 100 G's peak on the capsule, produced the most severe structural loading. Human tolerance to acceleration was studied by a survey of the available test data and a structural analysis of the human body. Test data for high-peak-magnitude low-total-energy acceleration exposures were not reported in the literature on controlled experimentation. Case histories of accidental falls and suicides were studied to gain insight into human tolerance to this type of acceleration. Several basic crew restraint concepts were evolved and evaluated. A concept employing rigid contoured support was selected to limit body-element displacement and distortion and to minimize rebound. A test system was designed and fabricated. Mechanisms were designed to preposition and pretension the crewman mechanically prior to impact. Further research should include thorough testing of the test system to determine the protection achieved by rigid contoured restraint. If high level protection is demonstrated, an operational prototype should be developed.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

Wayne H. McCandless
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ACCELERATION STRESS TERMINOLOGY

Several competing terminologies are currently in use for defining acceleration stresses. These differ in the phraseology by which they describe direction, in the specification of acceleration direction or the resulting reaction, and in the base or zero plane of reference. Descriptive phraseology varies from the obvious physical correlation expressed in the vernacular "Eyeballs Out, In, Up, etc.," to symbols understood only by specialists in fields such as structures, flight control or human tolerance. Acceleration direction is the primary interest of flight-mechanics engineers and the resulting reaction is important to restraint and structural designers. Accelerations which tend to change a vehicle's attitude or trajectory are frequently used in flight dynamics. The restraint designer must know the total or physiological accelerations incident on the crewman. This multiplicity of terms presents a language barrier that must be surmounted to report effectively on programs involving accelerations.

The Aerospace Medical Panel of AGARD has assembled and recommended a table of acceleration equivalents (Ref. 99). The "Physiological Computer Standard (Sys. 4)" listed in this table is used to define acceleration in this report. Symbols that will be used are listed below and referenced to other commonly used descriptive and vernacular terms. These symbols represent total accelerations.

Symbol for This Report	Other Commonly Used Equivalent Terms
$+G_x$, or $+G_x$	Forward, Transverse A-P, Sternumward, Eyeballs In, Supine, Chest to Back
$-G_x$	Backward, Transverse P-A, Spineward, Prone, Back to Chest, Eyeballs Out
$+G_z$, or $+G_z$	Headward, Positive, Eyeballs Down
$-G_z$	Footward, Negative, Eyeballs Up
$+G_y$, or $+G_y$	Right Lateral Acceleration, Left Lateral G, Eyeballs Left
$-G_y$	Left Lateral Acceleration, Right Lateral G, Eyeballs Right

SECTION I

INTRODUCTION

Crew restraint and support in advanced flight systems will require higher level protection than is provided by current restraint and support systems. Extending the basic concepts currently in use results in a complex system and does not fully utilize man's inherent tolerance to acceleration stress. New basic concepts are required to develop significantly improved crew protective devices. An understanding of the acceleration environment and the physiological and structural characteristics of man is required to generate these concepts.

This program was undertaken to develop a restraint system for protection against impact accelerations. Impact is defined (Ref. 61) as an acceleration pulse occurring so rapidly that the force input is over before the mass reacts to the force. Acceleration magnitudes were specified as 60 G in the $\pm G_x$ directions, 60 G in the $\pm G_y$ directions, 30 G in the $+G_z$, and 20 G in the $-G_z$ directions. These peak magnitudes are representative of capsule recovery impacts where the total velocity change is approximately 30 ft/sec and the acceleration profile is a sharp spike. This stress area has only recently been investigated by controlled testing and subjected to design analysis.

The program emphasized the fundamental approach to crew protection. Environmental stresses, operational requirements, and human capabilities were thoroughly investigated and correlated into design criteria before the conceptual hardware study was initiated. Current restraint and support systems were examined for possible solutions to portions of the problem; however, these were not considered to be necessarily adequate or representative of future systems. Unusual and unorthodox concepts as well as rigorously tested and service-proven strap systems were evaluated on an equal basis.

In establishing design criteria, quantitative data were used wherever they were available. When quantitative data were not available, assumptions had to be made. Many of the human characteristics data are based on assumption. However, they were derived from a thorough study of man's structure and the location and composition of his internal organs. They are, nevertheless, speculative in nature and must be treated as qualitative data.

SECTION II

MANNED SYSTEMS ACCELERATION ENVIRONMENT

Current and proposed manned flight systems were studied to determine the acceleration environment in which the flight crews would work. Data from a previous restraint requirements study (Ref. 96) were combined with flight dynamics studies of supersonic aircraft and space vehicles of both the ballistic and gliding reentry types. Unmanned space vehicles were investigated as a base line or control group to determine probable design G levels when crew safety was not a consideration. From the above studies and from discussions with flight dynamics specialists, it was apparent that manned flight systems are designed to limit accelerations to currently accepted human tolerance levels. None of the mechanical components and subsystems are considered to have an inherent G tolerance as low as man's currently demonstrated tolerance. Any increase in demonstrated human tolerance which can be accomplished by improved restraint-support techniques will therefore be immediately reflected in improved vehicle system performance.

Peak G level is only one of several factors that define acceleration stress. Rate of onset, duration at peak G, rate of decay, recovery time since last exposure, zero G preceding exposure, G direction, simultaneous application in two or more directions, and contributing stress producers (such as low oxygen partial pressure, vibration, heat and noise), all affect the severity of the exposure. These characteristics of advanced manned systems were studied to provide a better definition of anticipated stresses, particularly those stresses which would be new to the crewman's experience. Vibration, heat, and noise will be experienced more frequently and at higher levels than in previous flight systems. Low oxygen partial pressure may be experienced in emergencies. These contributing factors must be recognized and included to evaluate tolerance. Protection measures involving these stresses are not, however, within the scope of this program except in providing restraint-support devices that do not magnify vibrations.

Multidirectional accelerations and consecutive applications of acceleration stress will be more frequently experienced in advanced flight systems, particularly space systems. The many orientations a spacecraft must assume during a mission--buffeting and wind shear effects associated with hypersonic flight, high amplitude vibration of large boosters, parachute recovery in severe weather, and other operational characteristics of space flight--will produce a more random acceleration environment than aircraft crash loads. Large velocity changes, such as boost and reentry, will group these stresses into a series of multidirectional exposures occurring over a few minutes' time. These environmental hazards generate a personnel restraint requirement for substantial protection against many acceleration directions, including such heretofore rigorously avoided directions as $+G_y$ and $-G_z$. Furthermore, the protection required is substantially beyond that of a single pulse exposure.

Two highly significant stress areas were predicted by the study. One of these is the moderate-to-severe long-duration acceleration involved in large velocity changes. The cumulative G-time is fixed and cannot be changed. The G profile is related to the state-of-the-art in propulsion and reentry systems, and mission penalty is accepted to reduce G loads. Under the current technology, G levels of 6 to 9 G's for minutes and 20 G's for seconds are required for practical space systems. Much higher G levels are desirable from a vehicle design standpoint. The 6- to 9-G level boost profile stress area has been thoroughly investigated and found to be well within human limits for a trained test subject. The 20-G level, produced by escape from the pad beyond the atmospheric layer or by skipping reentry, is less thoroughly understood but is under investigation for current space-flight systems. Needless to say, both stress areas require extensive crew orientation and training. With the possible exception of liquid immersion, restraint-support devices protect a crewman against this stress area by supporting him in optimized orientation.

The second highly significant stress area is impact, with a high peak magnitude, high rate of onset, short duration, and rapid decay. This environmental hazard can be generated by explosion of the high energy fuels carried by spacecraft and their boosters. It is routinely produced by the landing impact of parachute-recovered capsule systems. Current recovery systems are small and structurally rigid to satisfy operational requirements. Impacting at vertical velocities of approximately 30 ft/sec, a low total energy acceleration is produced. Their stiff structure and angle of impact will, however, produce G spikes of 60 to 100 G's at rates of onset and decay of 3,000 to 20,000 G/sec. Current parachute recovery concepts may not be at all suitable for future primary recovery systems; however, sophisticated gliding, retro-powered, etc., recovery systems will probably depend on parachute-recovered escape capsules. Demonstrated human tolerance must be increased to this level, or impact attenuation devices will be required for future escape capsules.

Low total energy impact has only recently been investigated. Researchers' conclusions vary widely on human tolerance to such stresses. Some current theories postulate that the total energy, as defined by the delta velocity, is the predominant factor in impact. Such theories assume adequate support to preclude stress concentrations on vital areas such as the head. Tests with small animals and correlations of the limited human data available provide substantial support for the total energy theory. A recent correlation of test data, reported in Appendix II, indicates that unit pressure on the body predominates and that tolerable total impact energy decreases in the high G range. No comprehensive manned test data are available to verify these theories and only limited design effort has been expended to increase protection against such accelerations. We concluded that this stress area is the least understood and least researched of the two significant stress areas.

The predictability and probable warning times for severe accelerations in advanced flight systems were investigated to establish not only the level of protection that would be required continuously, but also the requirements for applying maximum restraint. Most of the severe accelerations can be predicted seconds to minutes before they occur. Boost, reentry, and landing are programmed into the mission. The highest probability of accelerations induced by malfunctions occurs in those regions where a crewman would already be restrained (i.e., boost, reentry and landing). Very light restraint will be required for the greater portion of the mission.

For the situation in which a malfunction, collision, or unexpected maneuver requires the application of restraint, suitable warning or automatic initiation devices must be provided. Possible parameters were investigated which could be sensed to provide such warning or initiation. The first parameter investigated was incident acceleration. Acceleration is the direct cause of danger and is easily sensed by human, electronic or mechanical methods. Both the magnitude and rate of onset can be sensed and the significance analyzed by computer techniques. The acceleration that must be applied by a positioning system to position the crewman by the time peak G has been reached was plotted against the rate of onset to determine if this method of sensing provided sufficient time to position and restrain the crewman (Figure 1). A uniform acceleration and deceleration was assumed for the positioning system. From Figure 1 it is apparent that for most anticipated rates of onset the positioning forces exceed the incident acceleration. It was concluded that causative factors will have to be sensed. Examples of causative factors are: unusual pressure buildup or rate of buildup in tankage or combustion chambers, unfavorable delta pressures on booster bulkheads, diverging flight path or instability, approaching collision, over-temperature, etc. This sensing problem is identical to the problem in developing warning devices and automatic initiators for escape systems. A sensing system of this type for the Atlas missile is described in References 53 and 90. A comprehensive study of detection and escape initiation devices has recently been completed (Ref. 28). It was beyond the scope of this program to engage in further study of sensing and initiation. The conclusion was that crew support and restraint devices should be initiated by an output signal from the vehicle escape detection and initiation system.

The foregoing study clearly indicated a requirement for the development of improved techniques to protect flight crewmen from multidirectional impact stresses. It further indicated that light, unrestrictive restraint would be sufficient for most of the flight profile if adequate warning, positioning, and restraining devices were provided. Protection against impact, prepositioning, and pretensioning were established as the primary design goals of this program. Major elements of the acceleration environment anticipated for future manned flight systems are illustrated in Figure 2.

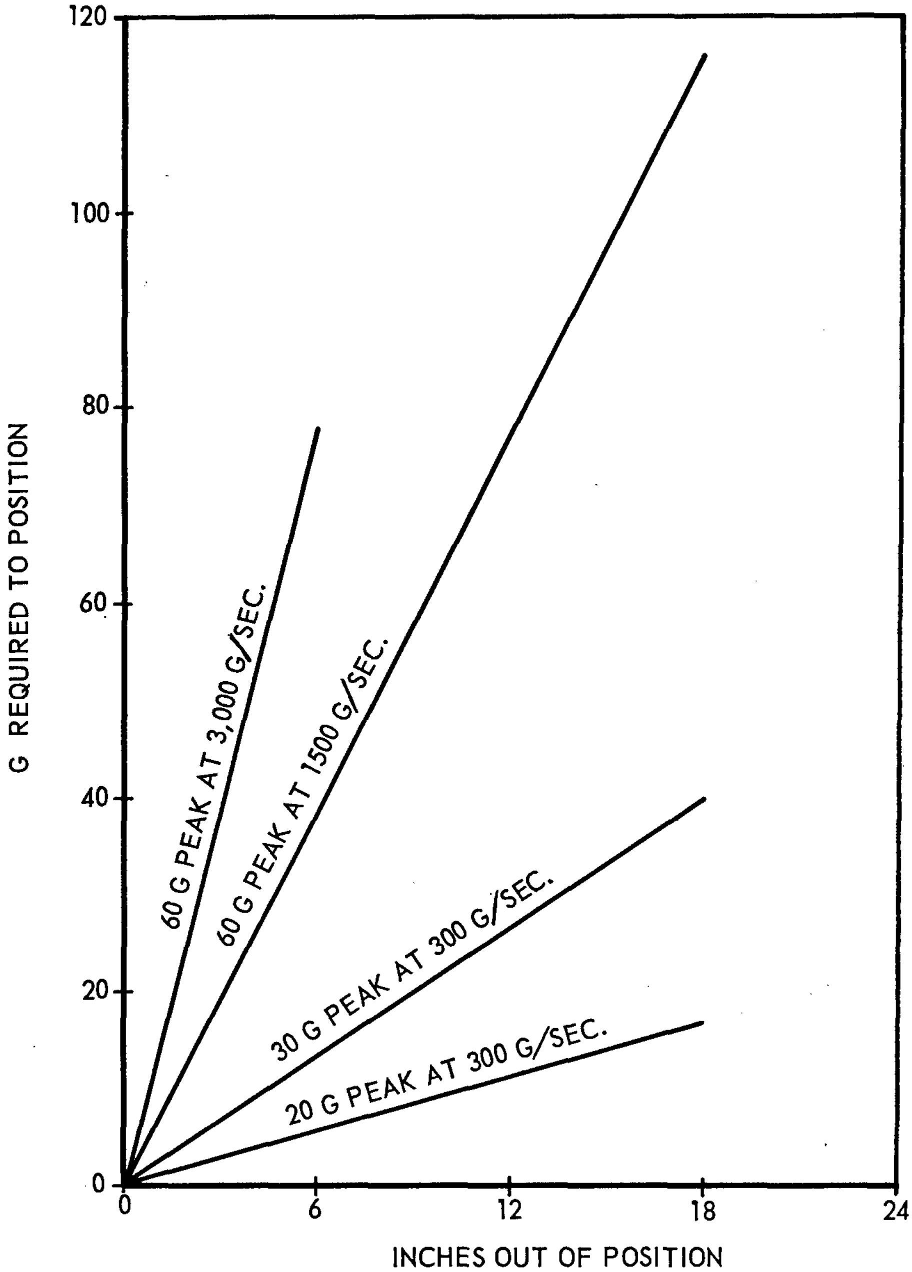


FIGURE 1 POSITIONING FORCES

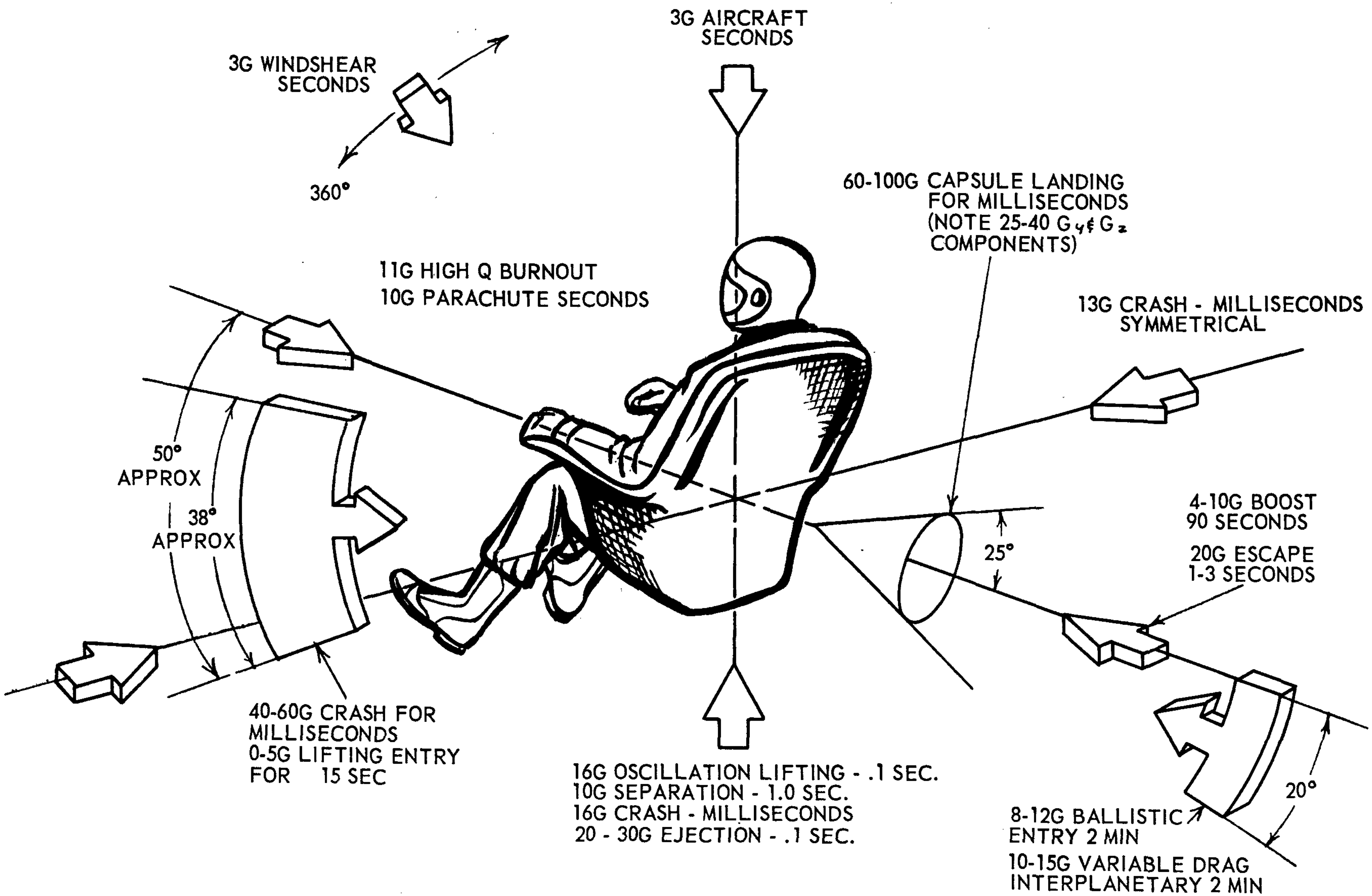


FIGURE 2 MANNED FLIGHT SYSTEMS SIGNIFICANT G

SECTION III

RESTRAINT SYSTEM OPERATIONAL REQUIREMENTS

Crew tasks and habitation requirements were analyzed to determine operational requirements for personnel restraint-support devices. Mobility requirements for low stress portions of the mission are similar to present-day high-performance aircraft or to any system in which a human operator is responsible for controlling a complex system. The crewman should have full freedom of his hands and arms as well as the capability of leaning forward from the waist to increase reach. He should have full freedom of the head for visual coverage of his displays and external vision. Foot and leg mobility requirements are less clearly established; however, the minimum requirement demands freedom of movement of all parts of the feet and legs to promote circulation and muscle tone. A new type of mobility requirement was established for high-stress portions of the mission. During boost, reentry, etc., the crewman will be required to exercise precise control of the flight system while protected at a level above current ejection-seat requirements. The restraint-support device must permit movements of the hands, wrists, and feet at the highest level of restraint. In addition, it must position the eyes for scanning critical displays and support the arms and legs to prevent inertial loads from actuating controls.

Comfort requirements are severe, particularly in space systems. Estimates on the time a crewman will remain seated or reclined in a restraint-support system vary from 8-hour shifts to several days. Either situation exceeds current duration requirements by a substantial margin. Under these conditions, comfort translates from a desirable goal to a vital consideration in terms of crew efficiency. This problem will be more apparent as space flight becomes more routine.

Ingress and egress requirements for supersonic aircraft and one-man orbital flights are similar to those for previous aircraft. Rapid ingress is desirable; however, if complex and time-consuming attachments and adjustments are required the preflight period can be used for the purpose and outside help is available. Egress provisions must permit rapid and reliable exit from the vehicle without outside help. For the multiplace long-duration flight systems now under development, entry requirements will likewise be more severe. Crew rotation and relief periods will require that the crewman perform the necessary attachments and adjustments in flight without help. If the restraint system cannot be easily and rapidly adjusted it will not be properly used.

Weightlessness will generate unique operational requirements. Although space stations may have artificially induced gravity fields, space-flight vehicles will operate most of the mission in a weightless state until continuous thrust propulsion replaces the current boost-coast systems. Initial orbital flights indicate that weightlessness is not, in itself, a significant physiological hazard. Tests utilizing the technique of immersing a subject in water for several hours and then exposing him to acceleration (Ref. 3) indicate that extended periods of weightlessness may decrease acceleration tolerance on subsequent exposure. Operationally, the absence of a gravity field presents many detail problems. The crewman must be supported in all directions to enable him to push and pull and to apply torque to the controls. He must also be restrained from floating into controls or structure. Comfort requirements under a weightless condition are difficult to define until more test data are available. Traditional comfort problems are: pressure points contacting the restraint-support system, and internal strains associated with poor posture. With all the loads removed, neither consideration is valid. The only comfort requirements clearly established for weightlessness were to provide freedom to move body elements and to avoid compressing or binding restraint devices. For long flights, special exercise equipment will probably be required.

Weight and bulk are critical factors in any high-performance flight system. It is axiomatic that the restraint-support system must have minimum weight and bulk in both concept and detail design. Weight and bulk of "worn" restraint components are factors in crew efficiency. Weight is not a direct factor within the weightless environment, but inertia and bulk remain unchanged. Power requirements for adjusting, positioning, restraining and tensioning the system contribute to the weight and bulk of the over-all system.

Equipment designed to be airborne for days, weeks, or months must be durable and easily maintained. Crew protective equipment is contained in the environmentally controlled crew cabin and is one of the less complex systems. These advantages are somewhat offset by lack of dualization and the necessity for a functioning system on return. This equipment must be capable of completing at least one mission with little or no chance of failure and with no maintenance.

One of the most significant operational characteristics of high-performance flight systems is the heavy work load placed on the crewman during the most hazardous periods of the mission. During boost, reentry, orbit insertion, rendezvous, lunar landing, and midcourse velocity corrections, precise control of the vehicle and close monitoring of subsystems will be required. To avoid adding to the crew work load and to assure crew safety, protective devices should be mechanically powered and preferably initiated automatically as a function of impending hazard.

SECTION IV

HUMAN STRUCTURAL, PHYSIOLOGICAL AND PSYCHOLOGICAL CONSIDERATIONS

The objective of this study was to bring forth by means of a physiological and anatomical review and analysis the strong points and vulnerable areas which must be identified in developing methods for protecting crews of advanced aircraft and space vehicles against acceleration stresses. Based on the results of the aerodynamic and space-mechanics analysis of the acceleration envelopes anticipated for advanced-flight vehicles, this study has been primarily directed toward protection against abrupt acceleration.

A. Literature Survey

Literature dealing with human acceleration tolerances or protection requirements and means was reviewed to secure background and to identify specific tolerance and protection data. Since the acceleration-protection design goals are above present tolerance limits, particular emphasis was placed on a review of the order and types of injuries incurred by subjects used in acceleration experiments and by victims of accidents involving abrupt acceleration and deceleration loads which could be quantitatively defined. Of great importance was the detailed human-anatomy study which was conducted to determine the vulnerable areas of the body, the mechanisms of natural protection, and the structural strong points which could be used to provide a means of applying artificial protection. Information gained in these studies was then used in formulating some general recommendations to help guide the design of restraint concepts and to define areas in which further investigation or experimentation was necessary for their verification and extension.

In spite of the relatively large amount of published literature describing man's tolerance to acceleration stresses, resulting both from experimental exposures and accident analyses, few fully usable quantitative values were found which could be applied in this design study.

This dearth of test data is not uncommon in areas of biological investigation in which man is the object of study, first, because of the inherent risks involved in such tests, and second, because of the natural differences in subject tolerance and experimenter technique. Such an area of testing involves an especially high risk as well as the element of humanitarianism which would be impossible as well as undesirable to remove. Results obtained from different investigators frequently do not correlate with any degree of confidence, especially when "pain threshold" is employed as a criterion or parameter in the experimental design. For example, in human-impact testing at Holloman AFB, the chest strap on which the accelerometer is mounted is adjusted in tension according to the pain threshold of the subject. As a result, the accelerometer readings and physiological functions (such as respiration rate and depth) are influenced by the pain threshold of the individual (Refs. 5, 6, 7 and 29).

Two recently published surveys of the literature are available in which general definition of human acceleration tolerance is provided (Refs. 29 and 96). These data have been used extensively during this study with other published data not included in the surveys. In the case of one significant series of tests, an effort was made to obtain more definitive data regarding the subject's anthropometry and the restraint harness design used (which was only generally described in the literature). Specifically, information was sought concerning the height, weight and build of the test subjects, with more detailed information on accelerometer location, harness adjustment, accelerometer calibration and the methods used in interpreting the recorded values. Unfortunately, information in this area had not been recorded.

A number of test facilities were visited to gather detailed data on human and animal tolerance tests. Acceleration traces from B-70 capsule drop tests were obtained from the Aerospace Medical Research Laboratory (AMRL) (Ref. 46). Movies of manned sled runs, X-ray pictures of animal runs, and some detailed records of human and animal runs were obtained at Holloman AFB. Navy ejection-seat data, including Martin-Baker seat-test traces, were supplied by AMAL and ACEL. These data were generally more definitive than could be obtained from the published literature, particularly when they were amplified by discussions with the experimenters and test subjects. Still lacking, however, was sufficient detail for a comprehensive quantitative analysis of human tolerance to acceleration.

The physiological significance of values recorded on accelerometers during tests of human tolerance to impact show fairly wide differences and has been a subject of considerable controversy. The primary reasons for these differences are variation in the location of the transducers on subjects and/or sleds, the rigidity of their mounting, the accuracy of calibration, and the techniques employed in reading peaks on the recordings obtained (Ref. 40). For example, many tests which employ chest-mounted accelerometers fail to measure the tension applied to the chest strap to which the transducer is attached. The necessity for obtaining accurate, standardized applied stress and human response recordings is now widely recognized. In 1960, AMRL began a series of government and aerospace industry seminars to define the problems in tolerance testing and establish uniform test procedures.

Although lacking the desired detail, many valuable acceleration tolerance data have been obtained and published. The degree to which we can use these data in predicting what might happen at higher exposure levels is limited only by the ingenuity employed in their application.

Using existing acceleration tolerance data to predict the effect on man of exceeding present limits, a unique approach was used. A calculation was made of the body surface area under a typical restraint harness as used in tests to establish existing limits. The force applied to this area was then computed, based on the mass of the various body segments supported by the restraint harness for the particular acceleration to which the man was subjected. Since measurements were not available for actual test subjects, statistically determined body segment weights and areas under the harness (Refs.2 and 5) were employed in the calculations. This procedure indicated that the area of the body under the standard restraint-harness supports pressures on the order of 40 to 50 psi without injury. The harness consisted of 3-inch-wide shoulder straps and lap belt with 1-1/2-inch-wide inverted "V"-crotch straps. This harness took advantage of the stronger portions of the torso and the pressures tolerated do not necessarily represent average tolerance values. If, however, pressures approaching these values can be tolerated over most of the torso, much higher accelerations might be tolerable with broader restraint.

As previously mentioned, in order to investigate human tolerance at higher acceleration levels, data from accidental falls were studied. DeHaven's analysis (Refs. 18, 19 and 20) of the acceleration stresses to which humans were exposed in several free-fall impacts indicates that man can tolerate impact stresses of astonishing proportions. Although not so dramatic, this inherent impact tolerance has also been demonstrated in acceleration tests, for the most part conducted with animals in which only minor injury was sustained. Even these injuries, when carefully studied, can often be traced to rather simple and widely recognized deficiencies in the respective restraint systems employed in the test. A survey of some of these injuries accompanied by anatomical support recommendations which may reduce the probability of their recurrence is included in Appendix I. This survey of injuries also partially served as a basis for estimating the vulnerability of parts of the body to injury.

Injuries described in the histories of accidental falls, experimentally induced animal injuries in severe acceleration tests and the limited history of injuries in manned testing were correlated to establish the most critical structural and physiological problems associated with impact protection. In almost all instances where high rates of onset and high peak G were experienced, some form of shock phenomenon was recorded. When the head impacted on a hard surface or sharp object, brain damage occurred. In $+G_z$ exposures, such as ejection-seat tests or nose-gear failures, vertebral injuries were encountered. Injuries to the internal organs or to their attaching membranes were encountered in some of the severe falls. Humans have survived accelerations conservatively calculated at over 100 G's without significant injury, indicating internal tolerance well in excess of currently accepted values. Their survival indicates that with proper restraint and support, demonstrated tolerance to impact can be increased. In this program, the apparent mechanism of protection in both controlled tests and accidental exposures was evaluated against human structural characteristics to determine logical protection methods. The human structural and physiological vulnerability analysis used for this purpose is outlined in Appendix I. In the following paragraphs, the vulnerability and basic protection requirements for each major segment of the anatomy are discussed:

B. Restraint Considerations for the Head and Neck

1. Structural Characteristics

The skull is a rigid bony structure possessing great strength (Refs. 56 and 57). Its strongest area lies in a plane from the vicinity of the eyebrows to the protrusion or bump on the lower medial occipital bone in back (see Appendix I). Primary positioning and restraining loads should be reacted in this region. A rigid, contoured head-restraint device bearing on this area would provide the highest level of protection by distributing the load on the skull structure. Below the plane of maximum strength, the bones of the head are not strong individually and unless several structures can be simultaneously employed in restraint they are useful only as locating and stabilizing points for the head restraint.

The brain, encased in the skull, is well protected against deformation. It is surrounded inside the head by the cerebro-spinal fluid with a density similar to the density of the brain. This system establishes an inertial balance under acceleration loading that retards movement of the brain. The brain may receive impact damage by deformation of the skull, rotation of the brain relative to the skull, and uniform reaction of the brain's inertia on the interior surface of the skull. The latter mechanism of injury occurs at the highest acceleration level. Maximum protection against structural brain damage is therefore achieved by minimizing locally applied stresses and angular acceleration of the head.

2. Hydrodynamic Aspects of the Head and Neck

In addition to the cerebro-spinal fluid, the head and neck have a copious supply of blood and lymph flowing through several large vessels and a very dense capillary system. If the shape of the skull is maintained, injury to the brain and sensory organs from impact results primarily from shock waves traveling through the cerebro-spinal fluid, brain tissues, blood, lymph and sensory tissues, and in long-duration accelerations, from hydrostatic pressure rise in these fluids due to their inertia. Retrograde flow is seen to occur under impact in the jugular vein and arterial pressure is greatly increased (Refs. 54 and 55). These shock-waves and pressures, transmitted through the circulatory network, may be sufficient to produce rupture of the small blood vessels throughout the brain and in the eyes. Retinal hemorrhage and black eyes suffered by Col. Stapp during his forward-facing sled runs at Edwards AFB and post-run headaches reported in $-G_z$ tests are postulated to be the result of this mechanism of injury. It was not possible, however, to determine to what extent Col. Stapp's injuries were aggravated by accelerations, over and above the basic test level, produced by whipping of the unrestrained head. Also, no test data are available on what movement, if any, is experienced between the eyeball and its socket.

It should be pointed out, however, that the flow of blood through ruptured capillary walls of the eye is so slow that immediate visual difficulties probably would not interfere with an intelligent escape attempt (Ref. 77). At the same time, it is entirely possible that rapid hemodynamic changes and trans-location of fluids is an important factor in neurological shock frequently noted to occur after impact deceleration experiments (Ref. 5, 6, 7, 8, 76 and 77). The increase in blood pressure in the carotid sinus regions brings about stimulation which, in turn, results in a reduction of heart rate and blood pressure (Ref. 9). This induced brachycardia and drop in blood pressure may be a factor in the development of a shock-like state, as best described in the report on Capt. Eli L. Beeding's 83 G deceleration run with a 3800 G/sec rate of onset (Ref. 8). Total delta velocity was not specified in the reference; however, the AFMDC Daisy track was used, indicating a velocity change of approximately 45 ft/sec.

An additional factor which must be considered in the interpretation of cardiac rate in deceleration experiments is the psychosomatic response to anxiety (Ref. 85). ECG findings of Nodal rhythm (Ref. 5,6, 7, 76 and 77) following experimental deceleration could have been partially induced by anxiety.

The exact mechanism of injuries in the head produced by hydrodynamic and hemodynamic changes associated with impact acceleration is not conclusively established (Ref. 56 and 57), but the fact remains that protection is required. The more classical and clearly defined hazards include the following:

a. Point-impact of the head on an object, causing deformation of the skull and related internal structures, is a hazard which has long been recognized.

b. Vertebral fracture and/or muscular damage resulting from impact acceleration force, particularly in $+G_z$ acceleration, or from extension of the neck when the head is restrained rigidly and not permitted to follow the torso.

3. Demonstrated Tolerance of the Head and Neck

Most of the test data relative to acceleration tolerance of the head and neck were taken with a minimum of head support and restraint. The subject's head was free to whip forward and down, rotate, rebound from the head rest, and experience elastic response due to the flexibility and elasticity of the head-neck-spine structure. Acceleration readings were frequently taken at the seat (input) structure or on some element of the body that was more rigidly restrained than the head. It was therefore probable that due to attenuation or amplification of the input force in transversing the elastic human body very different accelerations were experienced on the head.

$+G_z$ Acceleration

Much of the data on $+G_z$ accelerations have been accumulated in the testing and operational usage of ejection seats for aircraft. Ejection peak G's of 13 to 20 $+G_z$ have been demonstrated repeatedly although not always without injury. Early German experiments (Refs. 35, 83, and 84) indicated tolerance to 23 $+G_z$ without armrests and 28 $+G_z$ with armrests. It was not clear if these reported values were faired plateaus or short-duration peak values. In a more recent test (Ref. 48) a $+G_z$ value of 33 G was recorded on the head with a 16 $+G_z$ ejection-seat input. Such amplification of the acceleration experienced at the seat might be postulated to occur frequently during operational ejections.

Two significant observations are apparent from the recorded test and operational data. First, virtually no damage to the head and neck has been reported except by wind blast. Damage was primarily concentrated in the spinal column, with the inertial load of the head, neck, and helmet postulated to be a significant factor. Secondly, attenuation or amplification of the input force was probable, as the body was permitted to respond freely to the input acceleration.

From the above data and observations it was concluded that the head could withstand 30 $+G_z$ or more, experienced on the head as a short-duration peak acceleration. This conclusion does not imply that the whole man can withstand this stress level as a safe value. If the crewman's restraint provides poor spinal alignment and/or support, if a heavy helmet is worn, or if the head C.G. is not aligned with his spine, 30 $+G_z$ is probably not safe for the unsupported head.

$-G_z$ Acceleration

Limited testing has established -10 G_z at rates of onset of 60-80 G/sec with a total energy representative of ejection as safe for man (Ref. 29). Little difficulty was encountered at this level and no injuries occurred. It must be concluded that voluntary tolerance lies above -10 G_z and the threshold of injury may be well above -10 G_z. One experiment in $-G_x$ acceleration (Ref. 79) caused the subject's head to rotate forward and down, subjecting his head to -13 G_z for 0.6 seconds. A slight congested feeling was the only problem encountered. This congestion is the result of hemodynamic pressure increase in the head due to acceleration acting on the vascular fluid. In this case the column of fluid was much lower than in downward ejection, consisting only of the head and neck instead of the entire body. In all of the -G_z tests time was an important variable, with: -10 G_z tolerable for 0.004 seconds, -7 G_z tolerable for 0.1 seconds, and -4 G_z not tolerable for longer periods (Ref. 29).

$\pm G_x$ Acceleration

Input $\pm G_x$ acceleration of 30 to 38G have been tolerated many times in the development and evaluation of aircraft crash harness. The highest recorded -G_x exposure (Ref. 77) was a 45 -G_x input. In this test, as in most -G_x tests, the subject's head whipped forward and down. Approximately 40 G's were recorded on the subject's head, indicating an attenuating effect. The rate of onset was approximately 500 G/sec and the total velocity change was approximately 180 ft/sec. Shock was not induced; however, the subject suffered retinal hemorrhage and frontal headaches after the run.

The highest recorded $+G_x$ exposure in the literature is Capt. Beeding's 82.6 G for 0.04 sec at a rate of onset of 3800 G/sec (Ref. 8). These values were recorded on the chest during a sled run in which 40.4 $+G_x$ at 2139 G/sec rate of onset were recorded on the test seat. Acceleration was not recorded at the head which was supported by a half inch of felt over a steel plate and was free to rebound. No irreversible injury occurred; however, shock appeared to be present and the subject was not capable of performing duties for several minutes after the run.

Most of the $\pm G_x$ tolerance data were recorded in sled runs. Total velocity change was usually between 45 and 200 ft/sec. At these total energy levels an upper safe limit of 38 $\pm G_x$ applied at 1300 G/sec as indicated (Ref. 29). These indicated values result from faired curves taken from the recorded data. With lower total energy and abrupt spike-type acceleration exposures, high peak G might be tolerable. Unfortunately, little test data have been recorded in this stress area.

$\pm G_y$ Acceleration

Limited data exist regarding experimental exposure to lateral accelerations. Colonel Stapp exposed a chimpanzee to 30 G at a rate of onset of 930 G/sec without head restraint. The head was observed to rotate to the shoulder during impact without injury or apparent soreness being produced. Obviously, research on human tolerance to lateral acceleration is a virgin field with much work required.

4. Recommendations for Head Restraint

Positioning of the Head

Head positioning and orientation is first of all related to torso positioning and orientation. The head-neck mass center of gravity should lie on or close to a line through the center of the vertebra. This orientation utilizes the maximum column strength of the spine and provides the optimum bearing area for spinal disks (see Appendix I). Head orientation, relative to the applied acceleration, is an important consideration in reducing the magnitude of hydrostatic and hydrodynamic effects in the head fluids and pliable tissues. Holding the vertical axis of the head normal to the higher magnitude exposures will produce the minimum hydrodynamic effects on impact and the minimum hydrostatic effects under sustained accelerations.

Head Restraint and Covering

Head restraint should be applied to the maximum extent possible along the plane defined by the eyebrows and the occipital bone. For the highest level of protection or for protection from wind blast and foreign-object impingement, a rigid form-fitting protective covering should be used. It should be noted that the inertial load of the head restraint should not be permitted to add materially to the head inertia as the cervical vertebra is already critically loaded at the specified accelerations. The bones of the face and around the ears may be used for stabilizing the head but should not carry primary restraint loads. For $-G_X$ loads, the lower jaw is the best single stabilizing load path and can be reinforced by the upper jaw with the help of a teeth protector. Lateral head stabilization can be provided with broad support around the ears. To establish load paths, the center of gravity of the head and neck can be considered to be at the intersection of a line drawn from the bridge of the nose to the external occipital protuberance with a line drawn from the orifice of one ear to the other. Note that the C.G. is slightly below the plane of maximum strength in the skull.

Thus far, the site of injury occurring in the eye indicates that eye protection, other than against wind blast, would not be feasible since the injuries occur at the back of the eye bulb. As previously described, these injuries probably result from abrupt increases in blood pressure behind the eye. There is no indication to date that the bulb of the eye protrudes from the socket a sufficient distance to cause injury. Photographic coverage of eye response to acceleration tests would be of great assistance in determining the need for and methods of providing any necessary protection. Protection recommended at this time consists of preventing whipping of the head, minimizing shock loads such as occur in loose restraint, and orienting the head to minimize the fluid head. If future restraint consisting of actual retention of the eyeballs is used, it will have to be approached cautiously. External pressure applied to the eye produces a response similar to that of pressure on the carotid sinuses--that is, reduced cardiac rate and blood pressure.

Restraint of the Head and Neck Relative to the Torso

The neck is compatible with support of the head relative to the torso. Neck structure is not satisfactory for supporting the torso or any significant part of the torso from a fixed head. Head restraint provisions must provide flexibility that permits head excursions at least as large as excursions the torso will experience without imposing significant shear or bending stresses on the neck. For reasons previously stated, this flexibility should not permit the head to become loose in its restraint device or to impact on a hard or elastic surface.

C. Restraint Considerations for the Torso

1. Structural Characteristics of the Torso

The torso has the spinal column as its major structural member and may best be divided for the purpose of this study into the thorax and abdomen. The ribs branching off the spinal column provide a cage-like support for the thorax and part of the abdomen in the back. At the bottom of the torso, the pelvis forms support for the organs and viscera of the abdomen. The thorax contains the heart, lungs, and major blood vessels. Because of relative rigidity of the rib cage, compression is not appropriate in the restraint of organs contained therein. In fact, because of its strength, the rib cage can be utilized as a structural area for support, extending down over the abdomen if the force is broadly distributed. The strongest areas on the torso consist of the shoulder and rib cage and the crests on the superior anterior portion of the pelvic girdle. To utilize these points, the seat belt must be accurately positioned on the crests and the shoulder straps must be tightly tensioned to prevent rotation of the flexibly mounted shoulder structure. Also, the rib cage will distort under loading and the pelvic girdle will roll out from under the lap belt if the lower portion of the girdle is not retained.

2. Hydrodynamic Characteristics of the Abdomen

The abdomen, for the most part, is not supported by either bone or cartilage, but must be restrained externally. Under significant acceleration forces, the organs and viscera are seen to move as a semi-fluid mass (Figures 3 and 4). These figures show X-ray pictures of a dog taken during $+G_z$ acceleration. The abdomen of the dog, supported by the straps, can be seen to move through the space between the straps and form a protrusion. The most frequent injuries sustained in impact testing within the torso are those caused by rupture or tearing of the viscera. These injuries result from excursions of the organs beyond the limits of their attaching membranes, and from being stretched over and compressed against the restraint harnesses.

Protection of the viscera can be achieved by preventing distention of the abdominal cavity. Such support is satisfactory for horizontal accelerations, but its effectiveness in vertical

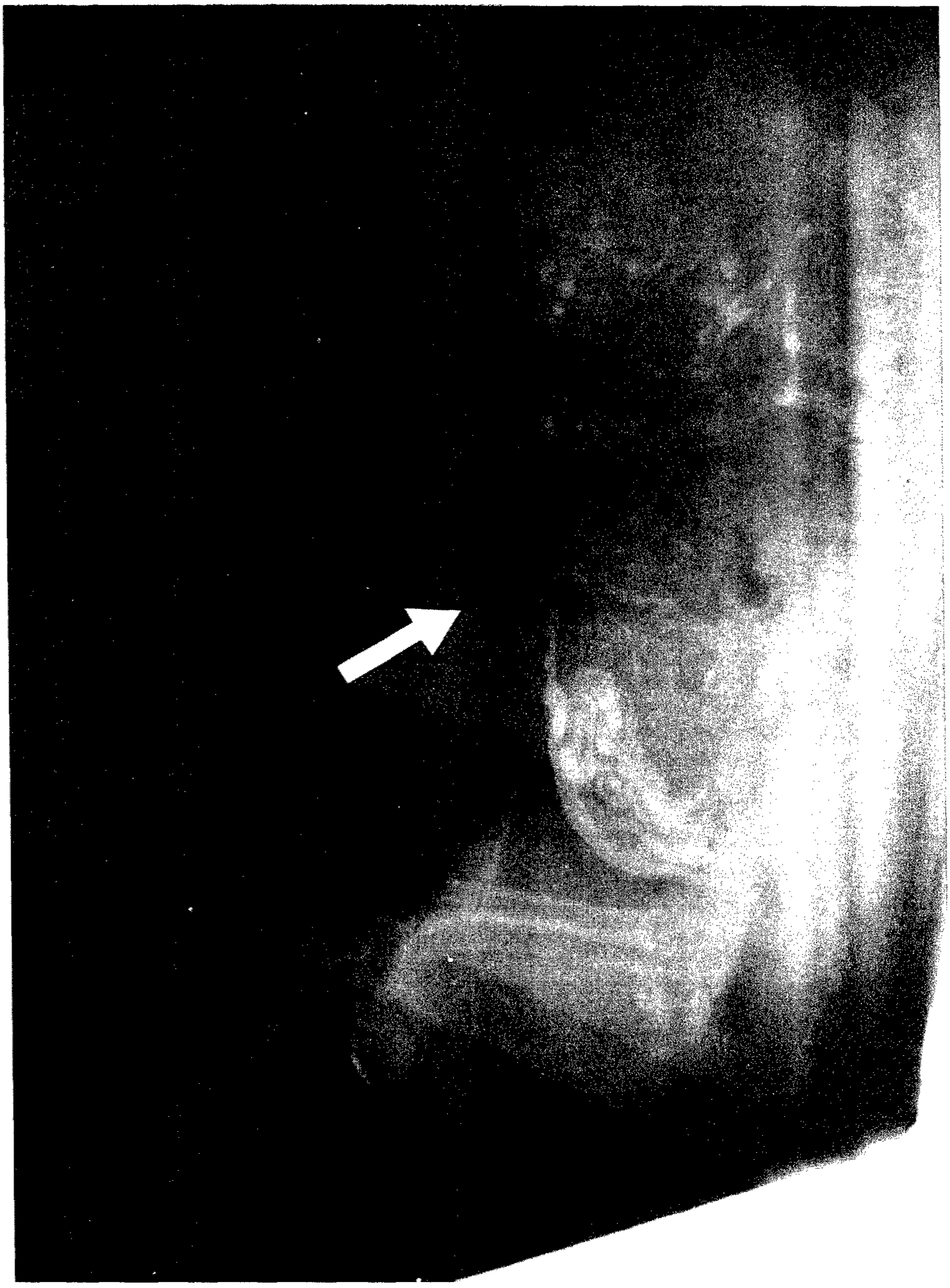


FIGURE 3 INITIATION OF ABDOMINAL DISTENTION

FIGURE 4 ABDOMINAL DISTENTION

restraint is doubtful. In $+G_z$ and $-G_z$ acceleration, the fluid flow of the viscera will be downward into the pelvic cavity or upward into the thorax, respectively. The more serious problem is in downward displacement. This is of particular concern because the natural protective tendency of the body is to slump forward, bringing the attachment points of the organs down to the nature support or limit imposed by the legs and pelvis. Such natural compensatory body movement may not be compatible with high-magnitude impact-acceleration body-positioning requirements, because vertebral alignment may be lost and the head moving free from its restraint would be subject to dynamic response. Three possible compromises are immediately apparent. These are: (1) using the "semi-fetal" position, i.e., to rotate the thighs and pelvis upward toward the organ attachment points; or (2) providing an artificial support for these organs; or (3) retaining the abdominal walls and depending on the semi-fluid viscera to support the upper organs on a fluid column. In addition to operational problems resulting from the semi-fetal position, the resulting spinal alignment is not normal for an adult male. Artificial support for the organs attached to the lower side of the diaphragm might be provided by constricting the soft abdomen at about the belt line. This mechanism would require testing, particularly in the application of a constricting device, because of the possibility of shock being produced by the force and movement applied to the viscera. Containment of the abdominal wall should be the initial mechanism of restraint and should significantly reduce the problem for both impact and sustained accelerations.

During maximum restraint application, the subject may be deprived of some of his breathing capacity because of the body compression applied to maintain optimum body alignment. This presents little difficulty for periods up to one minute. Fail-safe provisions, however, must be incorporated in the design to prevent this exposure period from being greatly exceeded.

Under very high $+G_z$ or $+G_x$ accelerations the areas over the inguinal canals in the groin may require local support to prevent hernia. This support may be obtained by the use of special appliances in a heavy-duty foundation garment. Some of the new devices used by athletes show promise for this purpose. No quantitative data are available, because of wide variability in individual susceptibility. Even if the injury occurred, it would not be debilitating, especially if good thigh support and a properly contoured seat are employed.

3. Demonstrated Tolerance

A postulated susceptibility to injury to the aorta has been described in Reference 96 (report by Goodyear). This injury is defined as a severance of the descending aorta adjacent to the cervical artery which occurs in abrupt $-G_y$ accelerations. Increased susceptibility would result when this vessel is caused to fill with blood by restriction of circulation. Such an injury would impose an important limitation to flight operations, since no means of supporting tissues in the thorax seems practical at this time. The conditions under which this injury occurs seem to be limited, judging by its infrequent appearance in aircraft operational accidents. An analysis of an accident in which a workman fell from a scaffold and impacted on his left side is reported in the literature (Ref. 43). Peak G was determined to be at least 162 G with a rate of onset of 22,000 G/sec. This man suffered no severence of the descending aorta; however, there was no occluded circulation on impact. Further study should be conducted on this possible problem to determine under what circumstances it occurs.

Captain Beeding's $+G_X$ run, in which the measured output acceleration on his sternum was in excess of 82 G for 0.04 sec at a rate of onset of 3,800 G/sec, is the highest tolerance demonstrated in controlled testing. It should be noted that the acceleration applied to the sled was 40.4 G. No permanent injury to the torso was experienced. Col. Stapp's exposures (Refs.5, 6, 7, 78 and 79) indicate tolerance to $-G_X$ accelerations of 45 G using modifications of the Air Force harness.

4. Restraint Recommendations for the Torso

Vertebral Support

The vertebrae should be maintained in an alignment that will produce the broadest bearing contact between disks. Lateral and longitudinal support should be provided for the spine; however, the support must fit the natural spinal contour and be sufficiently flexible to accommodate spinal compression without forcing the spine into an unnatural posture.

In this regard, a valid recommendation for crew selection purposes is made in Reference 96 (restraint devices report, by Goodyear), namely, that individuals with a lumbosacral angle of greater than 35 degrees in the semi-fetal position should be eliminated from duty involving high-impact acceleration. The semi-fetal position is defined as one in which the hips are flexed to 60°, knees flexed to 45°, ankles at 110°, elbows at 90° on armrest at side, back in straight relaxed position.

Much of the weight of the upper torso may be supported through the arms to an armrest. This support is important in relieving vertical loads on the vertebrae.

The above recommendations are valid for both impact and sustained accelerations.

Abdominal Support

No quantitative data on permissible displacement of viscera exist. From Figures 3 and 4, from film data on impacting rabbits, and from human $+G_Z$ and $-G_X$ accelerations endured without evidence of internal organ damage, a wide structural latitude is indicated. Other effects (i.e., shock, nausea and dizziness) may, however, be the result of viscera displacement. It is therefore recommended that the abdominal walls be reinforced in the front, back, and laterally from the termination of the chest cavity down to the pubic arch to minimize distention of the viscera. Such reinforcement provides the highest level of protection if it is produced by rigid contoured support which maintains the normal arrangement of the viscera. In the area of the lower abdomen and iguinal canals where rigid support is not recommended or feasible, firm containment of the level afforded by a heavy-duty foundation garment should provide the required protection.

The seating surface should be at least mildly contoured and tilted slightly upward from the line-of-action of the most severe $-G_x$ accelerations. Seat contour will reinforce the pelvic-femur sockets and minimize the possibility of prolapse of the rectum. Tilting the seat to the most severe $-G_x$ loads will direct part of the thigh and buttock loads into the seat. To reduce the loads on the ischial tuberosities inferior to the pelvic girdle, support should be provided under the greater trochanter (a bony projection on the femur opposite the pelvic joint). The pelvic girdle should be supported by bearing on the crest of the ilium. If a strap or other soft restraint element is used for this purpose it should be directed into the seating structure at approximately 45° to the x axis. Finally, for the $\pm G_y$ accelerations specified in this program, the buttocks and thighs should be firmly supported laterally.

The coccygeal vertebrae will provide little support if they touch the seating surface, and a painful injury can result. These vertebrae are best protected by providing an angle of less than 90° between the torso and thighs. An angle of 75° to 80° between the seat pan and seat back should prevent the coccygeal vertebrae from contacting the seat pan.

Thorax Support

The restraint device for the thoracic area must either be sufficiently rigid or otherwise designed to prevent deformation of the rib cage. If rigid structure is used to capsulate the torso, body structural points in this area may not be of importance; however, the area to which the standard USAF shoulder harness is applied remains the strongest structural area to support the upper torso. If a non-rigid restraint system is used, the area to which force is applied must be broad (or about three times the width of the existing restraint straps used in the standard USAF restraint harness).

Torso Orientation

Orientation of the torso at approximate right angles to the major long-duration accelerations will provide the highest physiological tolerance level for long-duration accelerations. This orientation also provides the largest bearing surface on which to react inertial loads generated by both impact and long-duration accelerations to minimize structural damage.

D. Recommendations for Restraint of the Limbs

1. Structural Characteristics

Elements of the arms and legs are not particularly vulnerable to acceleration-induced stresses unless they impact on a sharp object or the joints are bent in a direction in which they have limited flexibility. No major organs are contained in the limbs and the arteries are generally protected by heavy layers of muscles. Tight restraint can be applied over the limbs for approximately 15 minutes to the near exclusion of blood flow. The most significant loads imposed on the limbs will result from using the upper arm to assist in supporting the torso to relieve the spine in $+G_z$ accelerations and antisubmarining loads carried through the femur. No major problems are anticipated in these two areas if the elbow is not bearing on a hard surface and the antisubmarining loads are reacted at the patella and thence directly into the femur. The elbow and knee structures are illustrated in Appendix I.

2. Demonstrated Tolerance of the Arms and Legs

Quantitative data on limb tolerance have not been generated by manned tests; limb restraint was generally not employed. Even without restraint, virtually no damage has occurred. In aircraft and automobile crashes and in ejections, many limb injuries have occurred. These injuries can be grouped in three categories: Torso loads were frequently imposed on the limbs at impact. Flailing arms impacted on sharp objects. During ejection, powerful aerodynamic forces have forced limbs in the direction of least flexibility. (A frequent occurrence was forcing the arm back and rupturing the shoulder structure.) Most of these injuries could have been avoided with a bare minimum of limb restraint.

3. Operational Support of the Arms and Legs

Arms and legs provide the control inputs to the flight system and must be permitted sufficient mobility to accomplish flight control. In addition, they must be supported to permit control under acceleration loading. For $+G_x$ accelerations in excess of 10 G, the arm must be supported longitudinally to permit control, while support is desirable for much lower values if the acceleration is sustained. The lower legs can be moved at $+G_x$ values to 25 G; but, if control is to be effected by the legs or feet, support should be provided at much lower levels.

4. Recommendations for Restraint of the Limbs

Arm restraint should provide support for the lower arm to react the inertial load of the upper arm and part of the shoulders in $+G_z$ loading. This support should not impose loads on the nerve centers at the elbow. The upper arm should be supported against $+G_x$ accelerations to position and support the arm for flight control. Lateral support will be required at the $\pm G_y$ loads specified. Some form of restraint must be provided to prevent the arm from rising under $-G_z$ loads or flying forward during $-G_x$ loads. High protection levels will be possible with broad restraint; however, some compromises to this principle could be justified on the arms in the interest of operational efficiency. Any manipulating devices designed for arm positioning should avoid bending back on the shoulder and elbow joints and should not impinge the arms on sharp objects.

Leg restraints should include provisions for retaining the knees during $-G_x$ accelerations to support the inertial load of the thighs and lower pelvis. The restraining device should bear directly on the patella to provide a direct compression load path into and through the femur and thence to the pelvic socket. The same objective has been accomplished at low $-G_x$ levels with a strap below the patella which required transmitting the loads through the knee joint in shear. This approach is not recommended at the 60 G level. Lateral support of the thighs is recommended to react the thigh inertial load and reinforce the pelvic socket for antisubmarining loads. The calves should be supported to permit them to remain in contact with control devices. Broad restraint should be used over the area of the shin. The feet should be restrained relative to the calf; however, a high-top shoe might be sufficient and would provide ample mobility for the operation of toe controls. Restraint should be applied over the knee or the forward portion of the thighs and the calves under $-G_z$ loads to support the load and to stabilize the antisubmarining load path. Lateral restraint of the calves is recommended to prevent twisting of the knee joints and to position the feet.

Limb Orientation

For maximum tolerance to long-duration accelerations the limbs should be as close as possible to a plane through the heart and normal to the acceleration. This orientation also provides the maximum bearing area, thereby minimizing the danger of structural damage to the limbs.

E. Prepositioning Considerations

The tolerance of the torso and limbs to the application of restraint devices is a function of the area of body surface to which it is applied, the direction of application, and the inertial forces acting at the time of initiation. Movement characteristics of the joints are provided in Appendix I and in References 25 and 49. Restraint devices should incorporate movement restriction as required in limb positioning to avoid exceeding natural directional movement limitations. The rate at which the restraint devices can be applied depends largely on the details of their mechanization. Although these devices should be made safe for an unconscious crewman, a higher order of safety for the conscious crewman can be achieved by warning him in advance.

F. Future Test Recommendations

This section of the report has frequently cited the limitations which exist in quantitative values and the need for verification of various approaches to restraints recommended or suggested. In establishing requirements for future acceleration testing it is strongly recommended that these areas of the unknown be given consideration.

SECTION V

ENGINEERING ANALYSIS TO ESTABLISH DESIGN CRITERIA

Structural characteristics of the human body were analyzed to establish logical design criteria for restraint system design. Among the objectives of the medical literature search were the determination of stress limits in bone, pressure limits on human flesh, and tensile limits on ligaments, muscles, and tissues supporting the skeletal members and internal organs. Data on permissible sustained skin pressures were obtained from Reference 96. Limited data on spinal compression fractures were obtained from Reference 67. No quantitative data on organ attachment structure were located and the skin and bone data were not sufficient for a comprehensive stress analysis of the human body.

It was concluded that the engineers responsible for restraint design will have to understand the human body in a qualitative sense in order to develop and evaluate optimum restraint-support concepts. Manned testing will be required to verify that human structural limits have not been exceeded. Much of the data required for this training process are available in current medical literature. Life Sciences specialists located applicable literature and selected the required descriptions and illustrations for the engineers. A human skeleton, preserved human specimens, and anatomical models from Southwest Medical School were used to study load paths and vulnerable areas of the body. Working from these background data, logical load paths and body-restraint-and-support contact areas were determined. The results of this phase of the program are summarized in the following paragraphs.

A. Head Support

Head restraint has not been a firm requirement on previous flight systems. The neck structure has been sufficiently strong to restrain the head in most of the accelerations experienced. In addition, restraining the head relative to structure can cause the neck to transmit the inertial load of the torso or to be deflected into an unnatural and damaging shape. As a result of the above, little or no quantitative test data and very limited qualitative data are available on head restraint. Design criteria for the head were established by studying the skull structure and the relative movement that could be tolerated between the head and torso.

Preferred load-carrying areas on the skull were specified in Section IV as the plane from the eyebrows to the rear occipital bone for primary restraint loads, the lower jaw for longitudinal stabilization, and around the ears for lateral stabilization. The head-neck C.G. was specified as lying on a line between the centers of the ears. The head-neck mass was analyzed as a free body to determine a load path for the primary restraint loads that could be stabilized with a minimum force applied to the chin. It is theoretically possible to direct a strap or other restraining device over the forehead and back across the ears, reducing the stabilizing requirement to zero. This arrangement is unstable, however; and if the C.G. location is missed slightly, or the incident acceleration is divergent from the X axis, the head would rotate out of the restraint and impose bending on the neck. A maximum chin load of 200 to 250 pounds was postulated as safe, and the required angle for the primary restraint loads was calculated to be 35° below the horizontal plane. Loads applied to the lower jaw also produced an unstable situation, tending to rotate the jaw about its socket immediately behind the ear. This can be alleviated by directing the loads slightly forward of the ear and reacting the resulting moment into the fixed upper jaw through the teeth. A mouthpiece should be provided to avoid chipping of the teeth.

Relative motion between the head and torso is experienced in current restraint systems where the head is restrained by the neck. From movies of sled runs, a neck stretch of an inch or more seems to occur. Also, compression of the spinal column of up to an inch is experienced under + G_z loading, including one-G loads for extended periods. Neither observation guarantees that a man can withstand relative motions of this magnitude, applied in milliseconds, and forced into a set path by rigid restraint of the head and torso.

B. Torso Restraint

The rib cage and shoulder structure is a framework of pivoted and flexible bones and cartilage, held together with muscles and tendons and surrounding the air-filled lung cavity. This area provides no satisfactory localized attachment points that will distribute the loads to adjacent structure. The clavicle may be used for moderate loads if it is tightly gripped to prevent rotation; however, the loads must be transmitted through the sternum and rib cage to the upper spine which is itself a flexible object. It was concluded that thorax restraint should distribute the loads over the entire chest area and maintain normal chest contour to avoid pinching the lungs and heart.

The abdominal area is completely filled with soft organs attached by flexible membranes. These organs are similar to fluids in the case of excursions that do not impose loads on their attaching membranes. Although some gases will be present in the stomach and intestinal tract, the abdominal organs predominantly behave like a liquid. If distention of the abdominal wall can be limited so that the organs do not exceed their normal free movement range, the organs adjacent to the abdominal walls will support the deeper organs and the attaching membranes will not be stressed. Distension is readily prevented at the front and sides and is not a problem at the bottom and back. Upward excursions distend the diaphragm and are difficult to prevent. However, some of the most vulnerable and least flexibly attached organs, such as the liver, are attached to the diaphragm and are therefore not moved relative to their attachment when the organs move up and distend the diaphragm. Containment of the abdominal wall is recommended to protect the abdominal organs.

The pelvic girdle is a ring of heavy bones bonded together with slightly flexible joints and is the structural heart of the skeleton. The heavy lower (lumbar) portion of the spine is attached to the girdle at the upper rear portion, and the femurs are retained in sockets at the lower portion. This part of the skeleton is ideally suited to the application of restraint and should be utilized to the maximum extent. Two bony protuberances on the bottom of the girdle, the ischial tuberosities, are the normal load-carrying members of a seated subject and can carry much higher loads, as evidenced in ejection-seat tests. Two bony protuberances on the upper, forward portion of the girdle, the crests of the ilium, are the primary load-carrying members that are supported by seat belts in military aircraft. These crests can and should be used to hold the pelvis down and back.

C. Limb Restraint

Arms and legs are structurally well suited to restraint. Protection problems consist primarily of applying restraint with the minimum sacrifice to mobility. The heaviest limb segment, the thigh, imposes an additional problem. If it is not firmly restrained longitudinally, its inertial load will be transmitted to the lower portion of the pelvic girdle. Since the pelvic girdle is normally restrained by bearing on the crest of the ilium on the girdle's upper extremity, a rolling moment is introduced, generally referred to as "submarining."

D. Body Fluids

Body fluids, such as the blood stream, are subjected to hydrostatic and hydrodynamic effects on impact. Various shock phenomena and retinal damage, believed to be caused by this action, were described in Section IV. The design requirement is to minimize the intensity of the pressure. Hydrostatic pressure is minimized by crew orientation relative to the applied acceleration and thereby reducing the fluid head. Hydrodynamic effects are minimized by avoiding local sharp blows or jolts in excess of the applied overall acceleration.

E. Elastic Response

Both the restraint-support system and the crewman experience elastic deformation on impact, and the energy absorbed is returned in elastic response. In addition, the elastic and plastic properties of the man and system may prevent the crewman from following the acceleration-time profile of his impacting vehicle with a resulting "catching up" in which he exceeds the vehicle rate of onset and peak G. Readings of 1.5 to 2.0 times the acceleration experienced by the vehicle have been recorded on the test subject (Ref. 8). One protection mechanism is to stiffen the restraint-support system with higher modulus materials and stiffer types of construction.

F. Body Alignment

Many of the loads imposed on a crewman are carried through the body by column loading of skeletal members. In some instances, particularly in the case of the spine, a series of bone segments are subject to column loading as an assembly. Small deviations in optimum initial alignment in the compressed member or assembly will produce large increases in the resulting internal moments. Chipping or crushing of the edges of vertebrae is an example of such loading. Restraint-support systems conducive to proper posture will reduce this effect. Lateral support of the compressed member along its length will substantially increase its column-loading capabilities.

G. Body-Element Load Analysis

Structural damage to the human body may be anticipated if any body element moves a considerable distance relative to its adjacent element. Structural damage may also be caused by permitting the inertial load of an element to be carried through a joint to an adjacent element. Although some load transmittal between body segments is inevitable--for instance, the thorax and abdominal area--in general, an optimum system would support each element in space without relying on adjacent elements. One of the important parameters for designing a restraint-support system to a given acceleration environment is therefore the inertial loads generated by each body element at the specified G levels. These loads define the restraint component structural requirement and indicate the magnitude of the loads to be imposed on the surface of the element. The analysis was conducted by multiplying body-element weights from Reference 2 by the applicable G load in each of the six directions. Resulting inertial loads for a 95th percentile man are illustrated in Figure 5. Element weights for the 5th and 95th percentile man are also shown in the illustration.

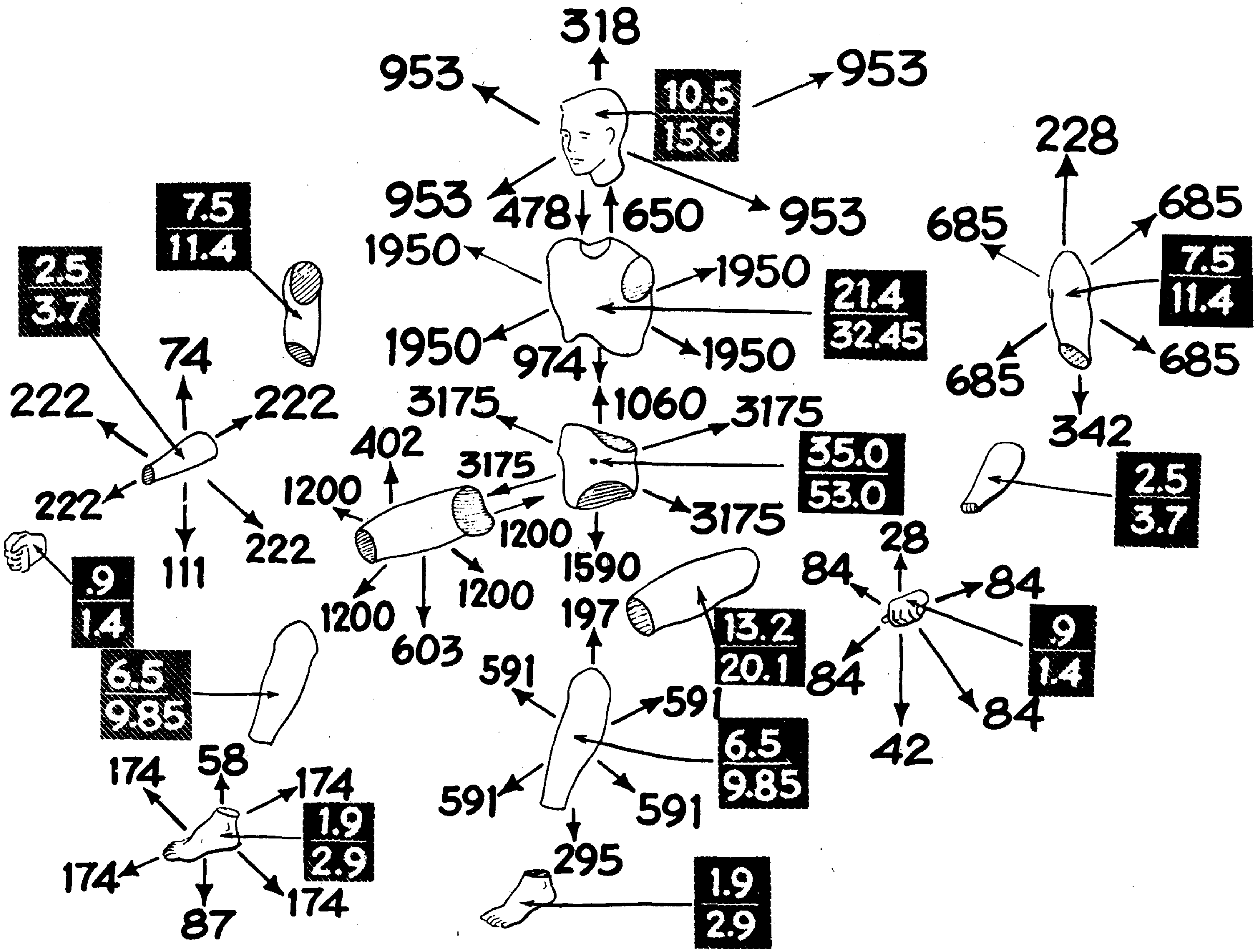


FIGURE 5 ELEMENT LOAD ANALYSIS

H. Element Unit Load Analysis

Restraining a body element without local injury requires careful selection of the contact area and sufficient surface contact on the element to prevent local crushing. An important parameter in restraint-support design is, therefore, the minimum unit pressure required to support a body element in equilibrium at the specified G level. To define this parameter, the element inertial loads were divided by element projected areas determined from Reference 41. This process required making some reasonable assumptions on the probable load carry-over across joints that occupied the element projected area in one or more directions. Also, in determining external pressure, compensations had to be made for large density differences, such as those which occur in the torso.

Head restraint under $-G_x$ loading illustrates the problem of assuming reasonable mechanics of restraint. Obviously, the eyes, nose and mouth should not be utilized as bearing areas, and previous studies had indicated a much higher load capacity for the forehead than for the small bones of the face. In addition, previous studies had established a requirement for a restraining area other than the forehead to stabilize the head, indicating the chin as best suited for this purpose. The forehead is assumed to carry 750 of the approximate 950 pounds inertial load of the head and neck to limit the chin to 200 pounds total force.

Torso restraint under $\pm G_x$ and $\pm G_y$ loads illustrates the variation in logical unit pressures due to the relatively high density of the abdomen and pelvic girdle compared to the air-filled thorax. Torso and thigh restraint also illustrates the effect of body segment joints wherein the large joint at the thigh makes it impossible to balance the moments on the pelvis without carrying loads through the thigh.

Figure 6 illustrates the results of this type of load analysis in the $\pm G_x$ and $\pm G_y$ directions. (G_y loads are symmetrical.)

I. Impact Attenuation

Acceleration forces incident on the crewman can be reduced relative to the vehicle accelerations by impact attenuation devices. These devices can not reduce the total energy incident on the crewman, as the total energy is directly related to the velocity change. They function by increasing the distance in which the velocity change occurs. If the attenuation device is installed between the crewman's restraint-support system and the vehicle structure, the system will move relative to vehicle structure on impact. The area swept through may be used as free volume in a crew cabin but cannot be used for storage or installation of equipment. Note that if protection is provided against multi-directional accelerations, a volume equal to the projected area times the stroke in each direction is compromised.

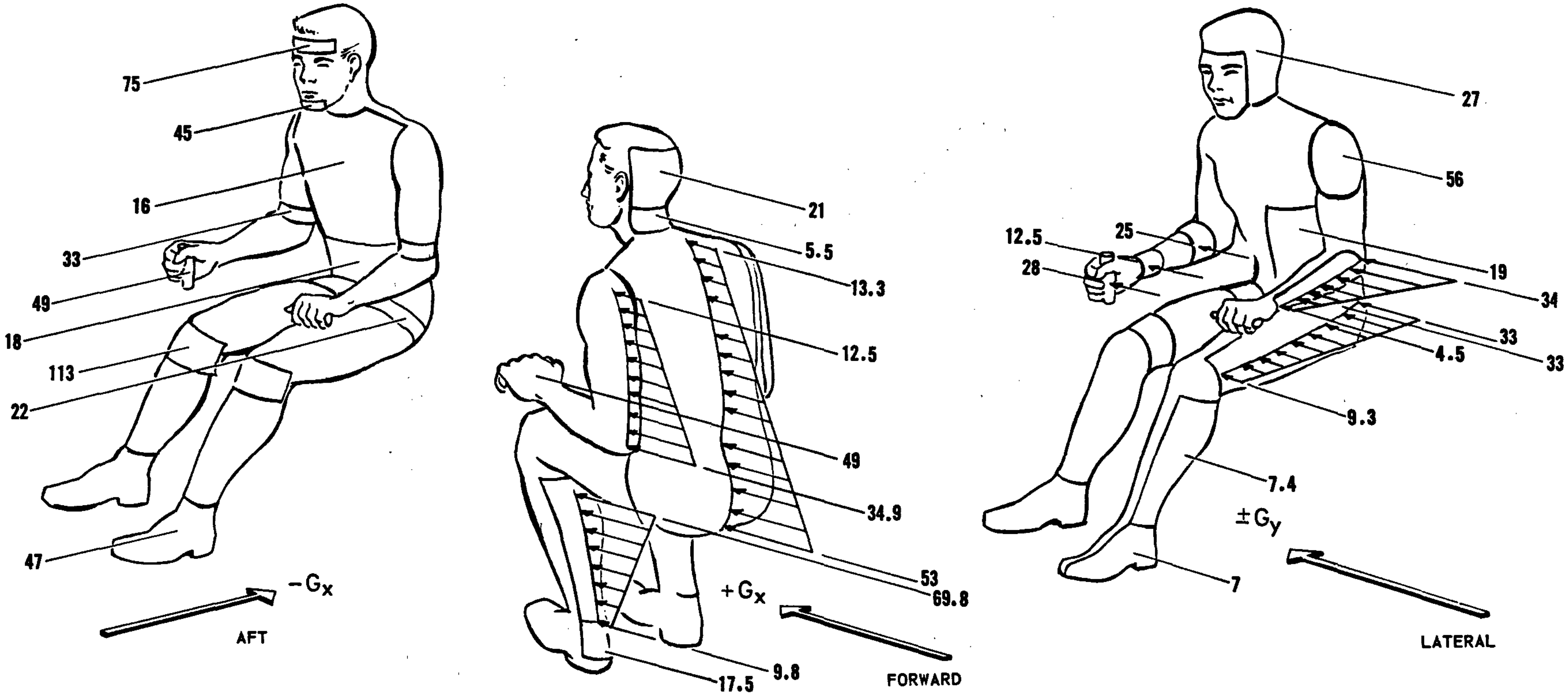


FIGURE 6 UNIT LOAD ANALYSIS

Figure 7 illustrates the stroke required to limit peak G on the crewman to various values, assuming the vehicle impacts at 30 ft/sec and experiences a peak of 100 G on structure. All exposures are assumed to be mirror-image spikes.

J. Design Criteria

From the foregoing analyses the following design criteria were established:

1. Primary head restraint loads should be applied at the forehead for $-G_x$ accelerations. Head stabilization restraint should be applied through the chin.

2. Head restraining devices should permit the head to follow torso movements.

3. Thorax restraint should provide broad coverage and maintain chest contour.

4. Abdominal restraint should contain the semi-fluid abdominal mass to minimize excursions of the abdominal organs.

5. Lower torso support should hold down and back on the pelvic girdle by retaining the crests of the ilium.

6. Submarining must be prevented by devices other than pressure on the lower torso. Support through the femur and knee and conventional crotch straps should be investigated.

7. Subject orientation and posture should minimize hydraulic head.

8. Sharp blows to any part of the body should be avoided. Loose restraint can produce sharp blows.

9. The restraint-support system elastic response characteristics should be rigid to avoid G overshoot.

10. Restraint-support components should maintain the crewman in a natural posture.

11. Skeletal assemblies subjected to compression should be reinforced laterally.

12. Restraint components should be structurally compatible with the loads established by the element load analysis.

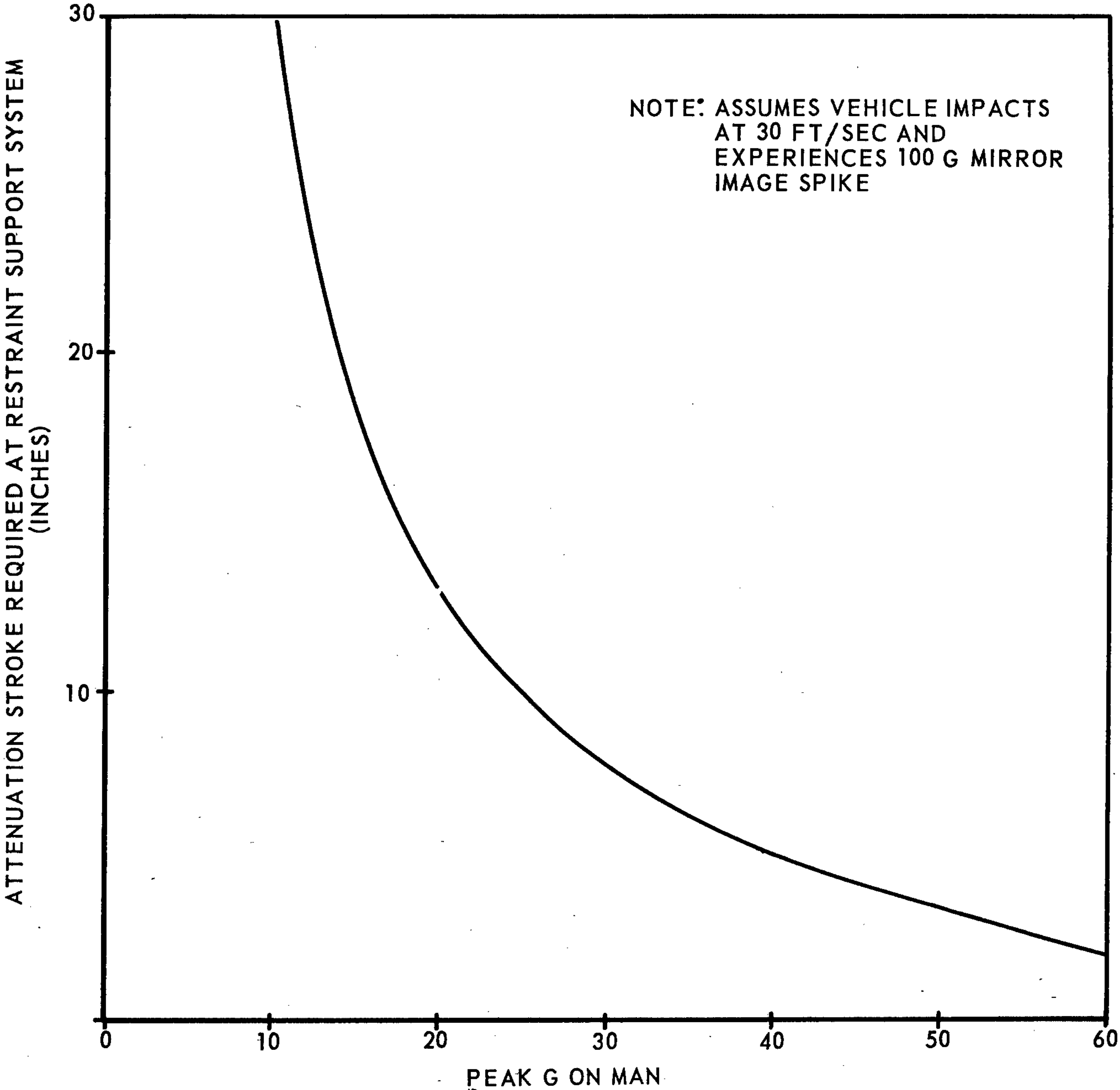


FIGURE 7 IMPACT ATTENUATION STROKE

13. Restraint concepts should be evaluated against logical unit loading for the restrained member, using the unit load analysis technique.

14. This program shall be directed toward increasing protection for a crewman who is subjected to the specified G's. Energy attenuation, if used, should be in addition to the specified G.

SECTION VI

MATERIALS INVESTIGATION

Concept development was initiated by investigating any materials that might have application to restraint. Properties of such conventional materials as nylon and dacron webbing, ensolite, leather, fiberglass, rubber, and metals were studied for possible new applications and to ascertain what characteristics provided their desirable and undesirable properties.

A. Conventional Materials

Nylon and dacron webbing are unusually versatile materials for securing irregular objects in place. Their flexibility, strength, and resistance to abrasion and deterioration are excellent. Disadvantages for application to personnel restraint include inability to maintain contour under load and low modulus, particularly in the case of nylon.

Ensolite has the best damping of any of the conventional materials and therefore the best rebound characteristics. It is comfortable for padding, light in weight and resists deterioration. Damping is not, however, as high as would be desirable for restraint padding applications.

Leather is useful for spreading out concentrated loads (such as buckles) over a wide area of the skin, and is sufficiently strong to maintain straps in position. It can be formed to irregular contours to provide a well-fitted, strong, protective covering. Despite its low rebound properties, leather is not considered suitable for primary load applications due to creep, variations in quality, and deterioration under some environmental conditions.

Fiberglass is useful for fabricating irregular contours with mechanical properties similar to aluminum but with somewhat greater quality-control problems.

Rubber has some damping properties but they are insufficient to overcome the disadvantages of its low modulus and elastic response when applied to restraining and padding elements.

Metals have a high modulus and, in the cases of aluminum and stainless steel, a high corrosion resistance. It must be noted, however, that metals have little damping and are almost perfectly elastic and that the effective modulus of the built-up structure is the ultimate consideration. Light metal structures in bending or metal sheets subject to oilcaning will have a low over-all modulus with an extremely high elastic response.

B. Unusual Materials

Unusual materials were investigated in an attempt to find materials, applications of materials, or combinations of materials that embodied the characteristics desirable in restraint hardware. Among the unusual materials investigated were: dilatant materials, paramagnetic particles in viscous solution, fluids, nylon Raschel net, wire screen, plastic foams, microballoons, materials that change state readily, foam-in-place materials, three-dimensional fabrics, and wire-reinforced nylon webbing.

Dilatant materials, marketed as a curiosity as "silly putty," have the unusual property of behaving as a viscous liquid under slow deformation and as a solid under rapid deformation. They were studied as a possible comfort padding with the rebound characteristics of a solid. The material was abandoned when it became evident it acted as an extremely elastic solid with almost no damping.

Paramagnetic particles in a viscous solution are used in clutch mechanisms. In the presence of a magnetic field, the solution experiences a large change in viscosity. From the investigation it was determined that the maximum viscosity was not sufficiently viscous to approximate a solid.

Fluid properties were of interest in that fluids might be contained in various devices to provide soft comfort padding, but if restrained from rapid flow would represent an approximate solid on impact. Most fluids have suitable elastic properties and weight-to-volume ratios are similar, with inherent weight as a major disadvantage. Selection of a working fluid would be based on hazard to the crew and compatibility with the environment.

Nylon Raschel net has been used in experimental support and restraint systems primarily for its comfort on long habitation and its ability to provide an automatic orientation change for long-duration accelerations. Elastic response on impact is very undesirable, and the net would have to be backed up by a more rigid material. A system using this principle is described in Reference 90.

Woven wire screen has been used on experimental crew seats to test comfort and practicability but has not been tested on impact. Comfort characteristics are encouraging and elastic response characteristics should be satisfactory. Attaching the wire to a rigid frame has proven difficult, and current seats are experiencing fatigue failures in the wire near the attachments.

Plastic foams, such as polyurethane, have lower response characteristics than foam rubber but are still too elastic and have too low a modulus for direct application. Open-celled plastic foams can, however, serve as comfort padding and flow damping on liquid-filled concepts.

Microballoons are small plastic spheres with a high electrostatic affinity for each other. When poured in a flexible container they flow like a viscous liquid and will readily assume any shape. If they are compacted within the container they become rigid. Application would be to universal fit, comfort and, in an emergency, to forming a rigid, contoured, support surface. They are extremely light in weight. In laboratory tests, compacting is accomplished by evacuating the container and using atmospheric pressure. This technique is slow, would be difficult to use in a cabin with low total pressure, and would be useless if the cabin lost pressurization. If the container size was sharply limited and microballoons could be pumped in, this concept might have wide application for in-flight use. To date, the problem of pumping small charged particles has not been solved.

Changes of state from a liquid to a solid, and the reverse procedure, could provide a soft or rigid surface as desired. A number of substances can be induced to change state by temperature change. Large amounts of heat must be transferred at low delta temperatures to produce the rigid condition. The time involved is prohibitive for impact protection.

Foam-in-place rigid plastics could be injected into an annulus surrounding a crewman to provide a form-fitting rigid garment. For an in-flight process this technique is faster than freezing, but is still slow for impact protection. In addition, substantial heat is released during the foaming process.

Three-dimensional woven fabrics were investigated as liners for contoured surface, close-fitting restraint components. Air circulation over the surface of the body will be desirable for long duration flights. Closed-cell padding materials (such as ensolite, or liquid-filled pads with impermeable surfaces) will limit air circulation. Ventilation liners to provide the necessary air space should be as thin as possible and have low rebound characteristics. A three-dimensional fabric, marketed as "Trilock," was investigated for this application. One of the many configurations of the material is currently used in exposure suits. The material looks promising for the application, with little tendency to respond to low-frequency vibration and less response to impact than open-celled foams. Elasticity would, however, still be a problem.

Wire-reinforced nylon webbing was reported as in use by a Swedish automobile seat-belt manufacturer. The manufacturer could not be located. This concept sounds promising. It should be noted, however, that the nylon would be a protector and contribute little to the webbing's load capacity, because of the difference in modulus. Also, woven substances, whether metal or fabric, have an over-all modulus lower than the basic material modulus; and this would be especially true if the wire were woven into the nylon.

SECTION VII

CONCEPT DEVELOPMENT AND SELECTION

Early conceptual design was concentrated on developing new fundamental restraint-support techniques for solving the detail problem areas. No attempt was made to develop over-all concepts or detail designs. At this point in the program very little evaluation was attempted. The objective was to compile a library of basic ideas for use on the subsequent design phases. Creative thinking methodology was used to assure retention of all ideas and concepts generated until they could be evaluated against each other.

A. Detail Concepts

A number of restraint-support problem areas are encountered in any conceptual or design study on personnel protection.

1. Operational effectiveness and comfort require a high level of crew mobility. Crew protection requires the minimizing of relative movement between body elements, broad support and restraint of the body surfaces, and selective orientation of the crewman relative to the applied acceleration. These important considerations generate a requirement for protective devices that do not restrict a crewman when protection is not required, with the capability of positioning, immobilizing and supporting him when protection is required. Several concepts were evolved to perform portions of this function. Several of these techniques relied almost entirely on material properties and were described in Section VI. Various types of pivoting seat back concepts were evolved and studied to provide complete torso protection while leaning forward in the seat. Raschel net or wire cloth on pivoted steel frames, pivoted fiberglass molded shells and conventional seats with pivoted backs were included. Designs that were based on selective fit included disconnects at the hips and shoulders with the torso protector worn from crew station to crew station. Back-scrubbing effects that plagued previous pivoted back seats were resolved in part by pivoting at the approximate hip effective pivot or entirely by a floating hip pivot mechanism that retracted to a fixed pivot point for crew prepositioning.

Head restraint and retraction devices that permitted mobility and protected against several acceleration directions were evolved. Some of these devices employed a hard helmet which was: retracted into a socket, captured by a scissors device, gripped by retracting arms or cables, or supported from the subject's shoulders by a trolley device that permitted turning the head. Another concept moment balanced the head-helmet mass with three-axis bobweights to permit the head to follow the torso while fully supported. All of the above devices were based on the assumption that the head could be retained in a helmet at the specified acceleration levels. This assumption was made to provide a basis for helmet-type concepts and is not a statement of a demonstrated or known fact. Soft head-positioning and restraint devices were developed to be compatible with a shirt-sleeve environment, reduce the inertial load of the helmet on the subject's head and spine and provide head mobility under load that would not force the neck into a dangerous orientation.

Arm mobility is required under most flight conditions and should not be compromised by restrictive retracting devices. For effective use, the arms must be free to bend in any plane at the wrist, elbow, and shoulder; and the crewman must be free to move his shoulders and upper torso to extend his reach and gain leverage. Various mechanical linkages, similar to human arm structure, were sketched out. Although concept evaluation was to be avoided at this point in the program, the "Mechanical Monster" properties inherent in this approach were too obvious to ignore. Pre-ejection type arm retractors were investigated for possible application to future restraint requirements. A typical pre-ejection system pulled a cable out of retainers on the sleeves and pulled the hands into the lap. The system had merit for the problem statement in ejection but was not suited for the situation where crew command of a flight system is required during and after full restraint. Multiple cable and strap systems were developed to provide the required protection but always at the expense of unfettered arm movement. Two methods were developed for "caming" or "wiping" the arm into the armrests by starting at the shoulder and working down. One of these methods used a zipper that started at the shoulder and zipped down to the wrist. In the other technique a strap was routed from the inside of the armrest, under the arm, over the shoulder and to the outside of the armrest. When the slack is taken out of the strap, it pinions the elbow to the armrests. A handgrip is required to stabilize the hand and lower forearm for $-G_z$ loads.

The requirements for leg mobility are not as clearly defined as requirements for arm, trunk and head mobility. Anticipated uses of the legs and feet range from their use as a power source through rudder and toe pedals to no requirement other than maintaining circulation. It was concluded that sufficient mobility to permit moving the thighs, calves and feet to maintain circulation and muscle tone was a minimum requirement. Positioning of all three elements of the legs can be accomplished approximately by cable or trolley retraction of the feet to a predetermined position. Several systems employing this principle were evolved. After retraction, folding leg covers would be positioned or a strap system would be tensioned. Another approach uses a knee and calf cover pivoted at the hip and rotating forward or carried on a linkage forward of the seat and moving back and down to pinion the knees and calves.

2. Providing individually contoured support without creating a major logistics problem is a problem area. Microballoons, foam-in-place, change-of-state, and net or wire cloth concepts are materials techniques to accomplish this objective. A system using nested hexagonal bars retained in a low melting point compound or a mastic was considered. Mobile restraint-support components that are personal equipment and readily portable between crew stations were studied as a partial solution to the logistics problem.

3. Antisubmarining protection has become more significant with multidirectional accelerations, forward-facing reentry, and relatively high decelerations of supersonic and hypersonic vehicles when power is terminated at high dynamic pressures. Current crotch strap configurations and similar crotch support devices were mocked up and their protection mechanism was checked by fitting them on humans. This type of antisubmarining device is presumed to support the pelvic girdle by bearing on the pubic arch. All configurations mocked up slid off the pubic arch and rested against the inside of the thigh when a few pounds tension was applied. It was obvious that crotch straps rely on the lateral strength of the hip socket in an outward direction. This mechanism has obviously been adequate for $-G_x$ accelerations tested to date, however, it employs a poor skeletal loading technique and is uncomfortable when worn for extended periods. Working from the previous study of the skeleton, both strap and rigid support systems were evolved to support the thighs and lower pelvic girdle through the patella, femur and hip socket.

4. Low-rebound, comfort-padding materials were discussed in Section VI. A build-up, low-rebound surface was investigated during this phase of the program. Open-celled polyurethane foam was encased in a liquid-tight liner which was in turn encased in a structural liner. The assembly was completely saturated with water. The soft foam provided comfort padding and viscous damping for the water during impact. A test sample was fabricated and proved to be quite comfortable. This surface will be referred to as LIQUIFOAM hereafter in this report.

5. Unborn mammals are carried in the mother's womb in a rolled-up or fetal position. It was postulated that this is a natural protective mechanism and might be an advantageous posture for withstanding impact. A crossed or basket weave strap system could pull the thighs up against the abdomen, calves against the thighs and the head down on padded knees. Obviously this technique does not permit optimum vehicle control or orient the spinal column of an adult human in the optimum posture.

6. Controlled pretensioning of a crewman prior to impact has been repeatedly demonstrated as beneficial during sled runs (Reference 77). A number of devices were investigated to accomplish this objective. Among these were: pulling a loop off center (bucket-handle effect), hydraulic and pneumatic bladders under straps or pads, and take up reels. It was not proposed to pretension to the impact loads as such loading for extended periods would be too severe. It should be noted that the tension build up vs. the restraint component excursion is non-linear and that most of the excursion occurs in compressing clothing and soft flesh and in tightening the weave in fabrics before appreciable forces are built up.

7. Broad restraint-support coverage of most of the body is desirable, particularly for the torso. Various cloth, web and pad devices were investigated. They included net vests, basket weave crossed straps, cloth tubes and rigid contoured pads. None of the net, strap or cloth concepts will maintain body contour under load, although

they can be designed to produce less distortion than current strap systems.

8. Orthopedic devices to reinforce and align the spine, position and contain the abdomen, and protect the inguinal canals have been in use for many years. These devices were studied to ascertain their design principles and for possible direct application. A concept was generated which incorporated all three protection mechanisms in one foundation garment. This foundation garment can be worn with soft restraint systems where it can also provide optimum positioning of the seat belt. It can also be worn under a rigid torso garment to protect the area below the garment's lower trim line.

B. Detail Concepts Evaluation

A preliminary evaluation of the detail concepts was conducted to eliminate techniques that could not accomplish the assigned function or which were clearly overshadowed by competing techniques. Raschel net seating was eliminated as incompatible with the primary purpose of the program--impact protection. Head restraint devices that do not permit the head to move and the neck to bend to accommodate torso movement were eliminated. Articulated mechanical devices following the arms were eliminated because of their weight, bulk, complexity and interference with crew movement. Crotch straps were eliminated because of the undesirable load path they employed. Use of the fetal position was eliminated because the protection gained was not considered sufficient to justify the loss of mission command capability.

C. Over-all Concepts Development

Some of the detail concepts retained for the over-all development phase appeared promising for the solution of major restraint-support problem areas, but were obviously not compatible with all of the design objectives. In addition, engineers and Life Sciences specialists on the program had undoubtedly acquired preferences in developing the detail concepts. It was evident that if over-all concept development was allowed to proceed at the discretion of each designer, some of the important design goals would not be thoroughly investigated. It was equally evident that requiring each system to emphasize all design objectives on the same basis would sharply limit the number of concepts exploited and presented for final evaluation. The following concept development procedure was used to assure broad coverage of the subject.

Five primary design goals were established as major system objectives and a designer was assigned to each goal. His instructions were to optimize the specific goal in a complete system with the minimum sacrifice to other important goals. This procedure assured primary consideration of five of the most important objectives and at least five secondary design efforts in support of each of the other objectives. The five full systems and an integrated foundation garment developed by this process are described in the following paragraphs:

1. Minimum Encumbrance "Caterpillar" Concept (Figure 8)

This concept was developed with the objective of unburdening the crewman as much as possible when his restraints are not in use. While the encumbrance of the restraints have been minimized, requiring probably only a lap strap or a version of the integrated foundation garment (Figure 13) for positioning under weightless or $-G_z$ conditions, the annoyance of limb retracting cables remains. It may also be necessary to provide a light shoulder harness and some form of head positioning device to locate the head and torso prior to positioning of the restraint.

The system employs inflatable fabric bags or bladders supported by semi-circular metal formers. The latter are attached at the ends to slides operating on tracks, similar to the sail slides on the mast of a sailboat. In the stowed position, the bags are collapsed and positioned out of the way. The bladders for the lower legs and for the lap are stowed above and forward of the knees. The forearm bags which travel on tracks along the armrests are stowed forward of the hands, and might surround any hand control devices. The bag for restraint of the torso and upper arms stows above the head, as does the head restraint bladder. Closed cable systems extend or retract the restraint bladder formers along the guide tracks. After positioning, the bladders are inflated to provide restraint, pressing the body and limbs down and aft into the seat and armrests.

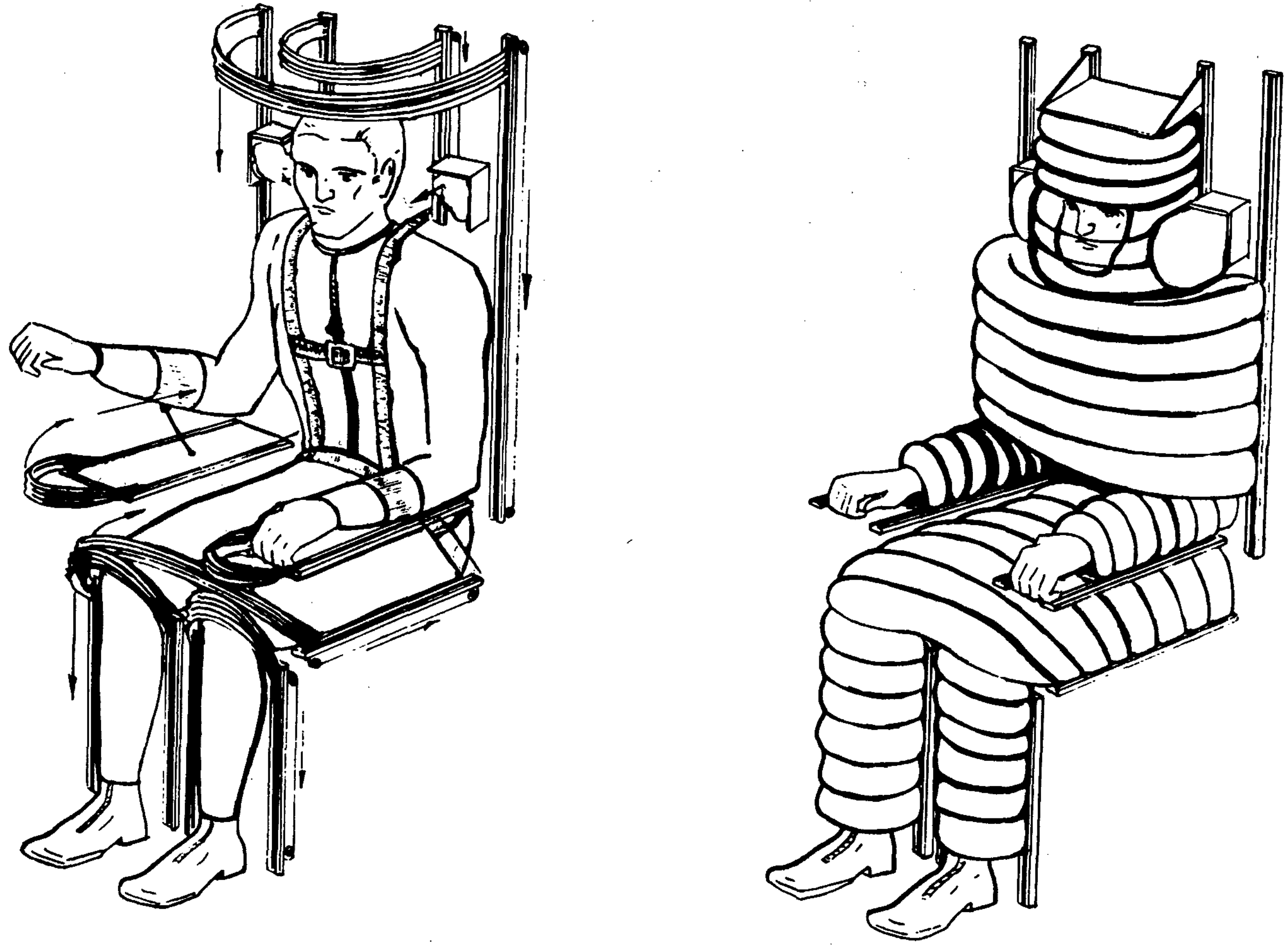
Various segments of the system could be operated independently to provide lap and torso restraint while leaving forearms and lower legs free. Head restraint can be independent of torso restraint.

Small spherical bladders mounted above the shoulders assist in holding the torso down during negative accelerations and provide added lateral support for the head. A knee harness may be required for antisubmarining.

Upon actuation, the lower leg bladders move down over the legs, and the lap bladder moves up over the thighs. The torso restraint moves downward over the body and upper arms where it joins the forearm bladders which move up over the hands and forearms. The head bladder moves down over the head, while an air bag over the head is in position. Varying the inflation pressure of the system can be utilized to provide different levels of restraint.

An opening in the front of the head restraint bladder is provided for breathing and for vision.

This system may be suitable for application to many types of seats, and could be used for the Mercury couch by mounting tracks on the forward surfaces of the couch.



NORMAL FULL RESTRAINT

FIGURE 8 CATERPILLAR CONCEPT

2. Universal Fit--Soft Harness--Seat Mounted (Figure 9)

This sytem is designed to provide broad, low unit pressure restraint in an adjustable, seat-mounted harness system. The crewman enters the vehicle or rotates crew stations wearing nylon flight coveralls with an integrated knee antisubmarining strap system and a sized head harness. All additional items required for his protection are mounted on the seat. The seat is a universal model utilizing microballoon cushions to provide seat and back contour. The seat back pivots about a floating point on the seat pan to permit the crewman to bend forward at the waist while still locked to the seat back. Lower leg rests are adjustable fore and aft for fit.

Torso protection is provided by a nylon net garment extending from the top of the thighs to the armpits. The garment has a zipper front closure and a lacing system that tightens the net around the torso when the four torso hold-back straps are retracted by the automatic tightening system. A tiedown locks the torso garment to the seat back along the entire length of the back. Four straps are attached to the front of the garment and the torso hold-back straps. They are adjusted to short out the body squeezing action when the desired tightness of fit is attained and will carry the torso forward inertial loads. A seat belt is integrated with the torso garment to maintain alignment over the crests of the ilium. Broad shoulder straps are integral with the garment and are carried aft through adjustable height fittings. Tiedown straps from each side of the garment are fastened to the seat pan. All of the aforementioned tiedown straps are firmly pretensioned by the automatic tightening system prior to impact.

Forward inertial loads are carried by the four torso hold-back straps, the two shoulder straps, and the seat belt with the tiedown straps preventing the garment from rising. The tendency of the body to flatten will be reduced by the squeezing action and the broad, tight abdominal covering will minimize abdominal distention. Lateral loads will be taken by the back tiedown and the torso hold-back straps. Negative loads will be supported by the shoulder straps, tiedown straps, and back tiedown. Positive loads will be taken by the seat cushion while the shoulder and hold-back straps, the back tie-down and the squeezing action maintain spinal alignment and retain the viscera. An athletic supporter with inguinal hernia pads is worn under the flight suit.

Head restraint is provided by a sized strap system, a head back rest and hinged lateral support pads that fold back when not required. The head harness uses dacron straps for load paths and dacron net and small straps to position the load path straps. Dacron straps attached at the intersection of the head load-path straps are automatically tensioned by reels before the onset of acceleration. Two or three Christmas Candy loops in the hold-back straps are maintained by elastic and permit limited head movement.

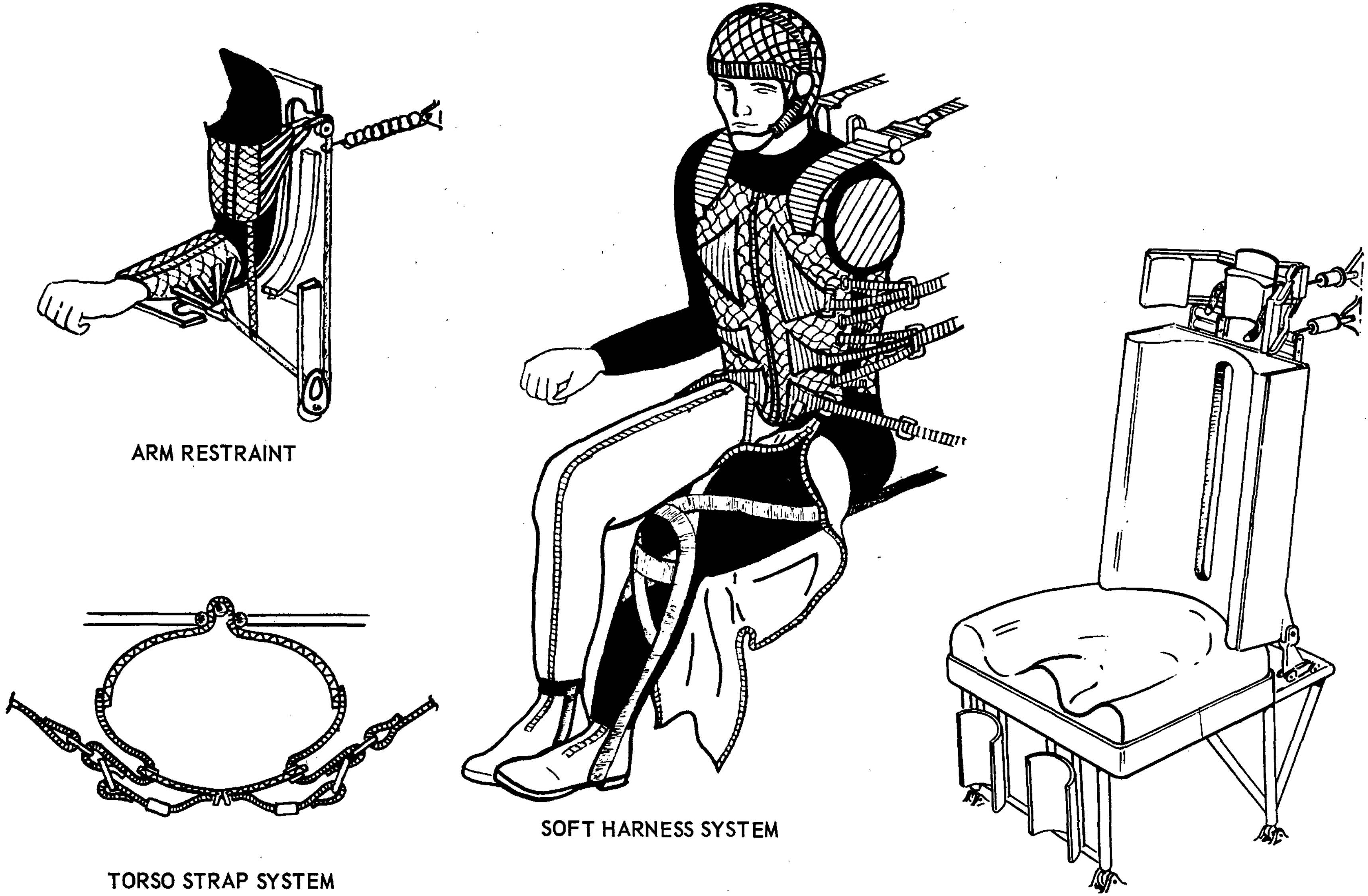


FIGURE 9 UNIVERSAL SOFT HARNESS

Forward inertial loads are resisted on the forehead and chin. Lateral loads are resisted by the side flaps acting over a broad surface on the side of the head. Under vertical loading, the head is free to move up or down within limits set by the hold-back strap attachment points. Little or no vertical head restraint is provided and very little weight is added to the head by the head harness.

Arm restraint is provided by laced upper and lower arm cuffs with zipper closures. The lacing ends are gathered together and attached to the repositioning and restraining cables. An elastic band holds the lower positioning cable at the elbow to prevent it from dragging across controls. A lever mechanism rotates the attaching cables from a position near the shoulders to a position below the armrests to reposition and tighten the restraint. The cables pull the arms against the armrest and tighten the cuffs.

Forward inertial loads are resisted by the upper cuff directly and by the lower cuff by friction. Aft inertial loads are carried into the upper armrest. Lateral loads are resisted by the curved armrest and negative loads are restrained by the lower arm cuff directly and the upper arm cuff by friction. Positive loads, including part of the shoulder and upper torso loads are supported by the lower armrest.

Leg restraint is provided by a knee-antisubmarining-integrated-strap system and by a zipper closure fabric tube attached to the seat. The zipper halves are brought together after the crewman enters the seat. When the system is initiated, a cable or track device pulls the zipper slide down, positioning and restraining the legs.

The knee strap system, which is tightened at the rear of the seat pan prior to impact, prevents submarining by holding the femur into the pelvic socket. The pelvic socket is reinforced by the form-fitting microballoon seat cushion that also relieves the load on the ischial spines and prevents prolapse of the rectum.

3. Integrated Soft Harness Restraint System (Figure 10)

This sytem is designed to provide broad, low unit pressure restraint in a universal, fixed back seat. The torso concept described in System 2 is integrated into a sized garment to produce a more optimum fit with fewer adjustments and less bulk. The crewman enters the vehicle or rotates crew stations wearing an integrated suit and harness reinforced with dacron net and a form-fitted helmet. The seat has a flat seat pan, flat fixed back, and provides universal fit by utilizing microballoon cushions or water-saturated polyurethane foam. Lower leg rests are adjustable.

Torso protection is provided by the nylon coveralls reinforced with straps and dacron net. Lacings on each side squeeze the torso when the two torso hold-back straps are tightened. The squeezing action is shorted out by tailoring or preadjusting the lacing length. Long buckles on each side carry all lacings to a

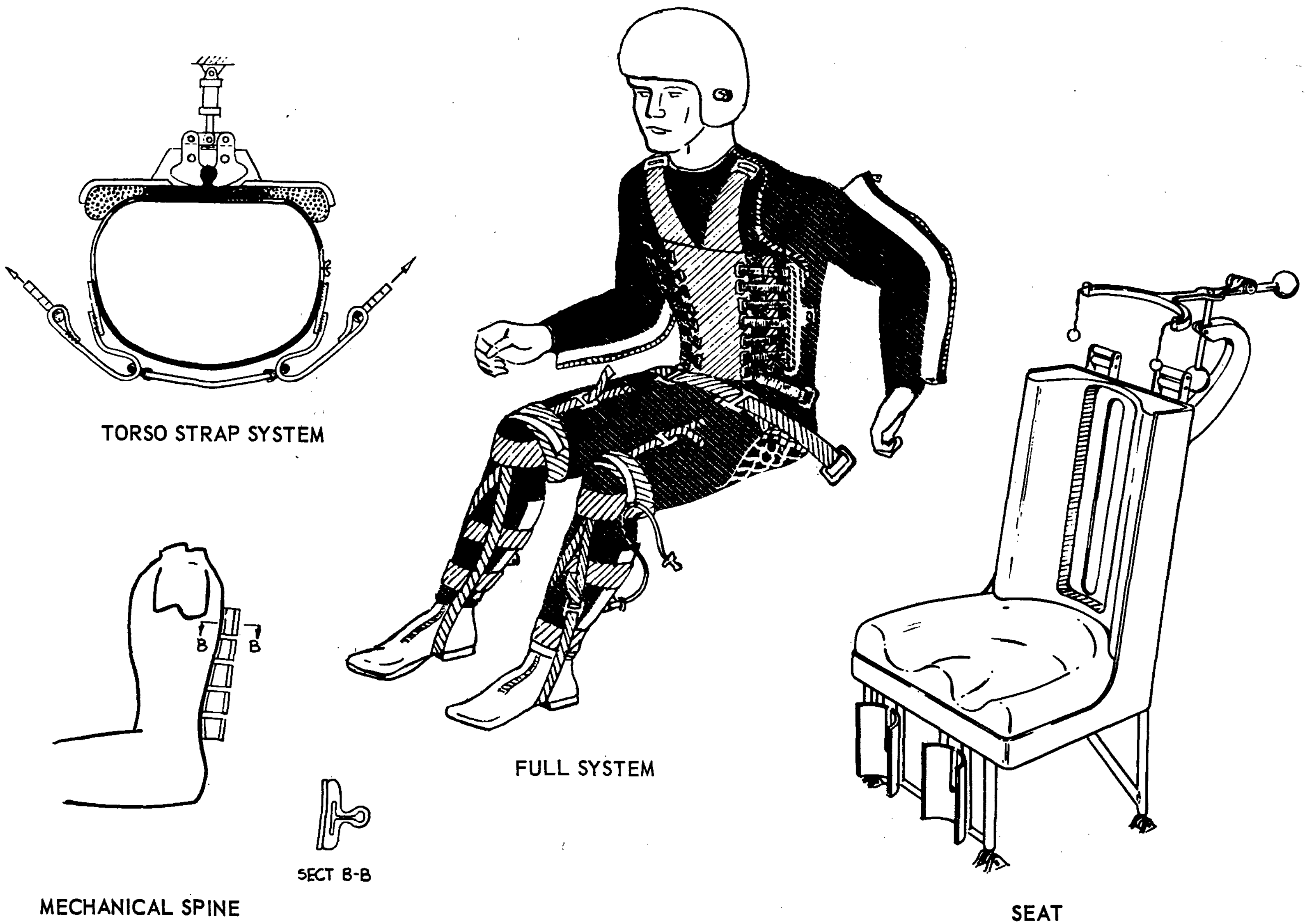


FIGURE 10 INTEGRATED GARMENT CONCEPT

single strap to minimize the number of straps that must be extended to lean forward. The zipper on the coveralls is located on the side to remove it from the 60 G load path. The shoulder straps and lap belt are similar to System 2. To permit forward torso movement, the back tiedown must be disengaged from the seat. This is accomplished by integrating a segmented mechanical spine into the flight suit. When the shoulder and torso hold-back straps position the man in the seat, an overcenter cam mechanism locks on the spine, rigidizing and supporting it to the seat back. Protection is similar to that of System 2 except for the greater protection of selective fit. An athletic supporter with inguinal pads is worn under the suit.

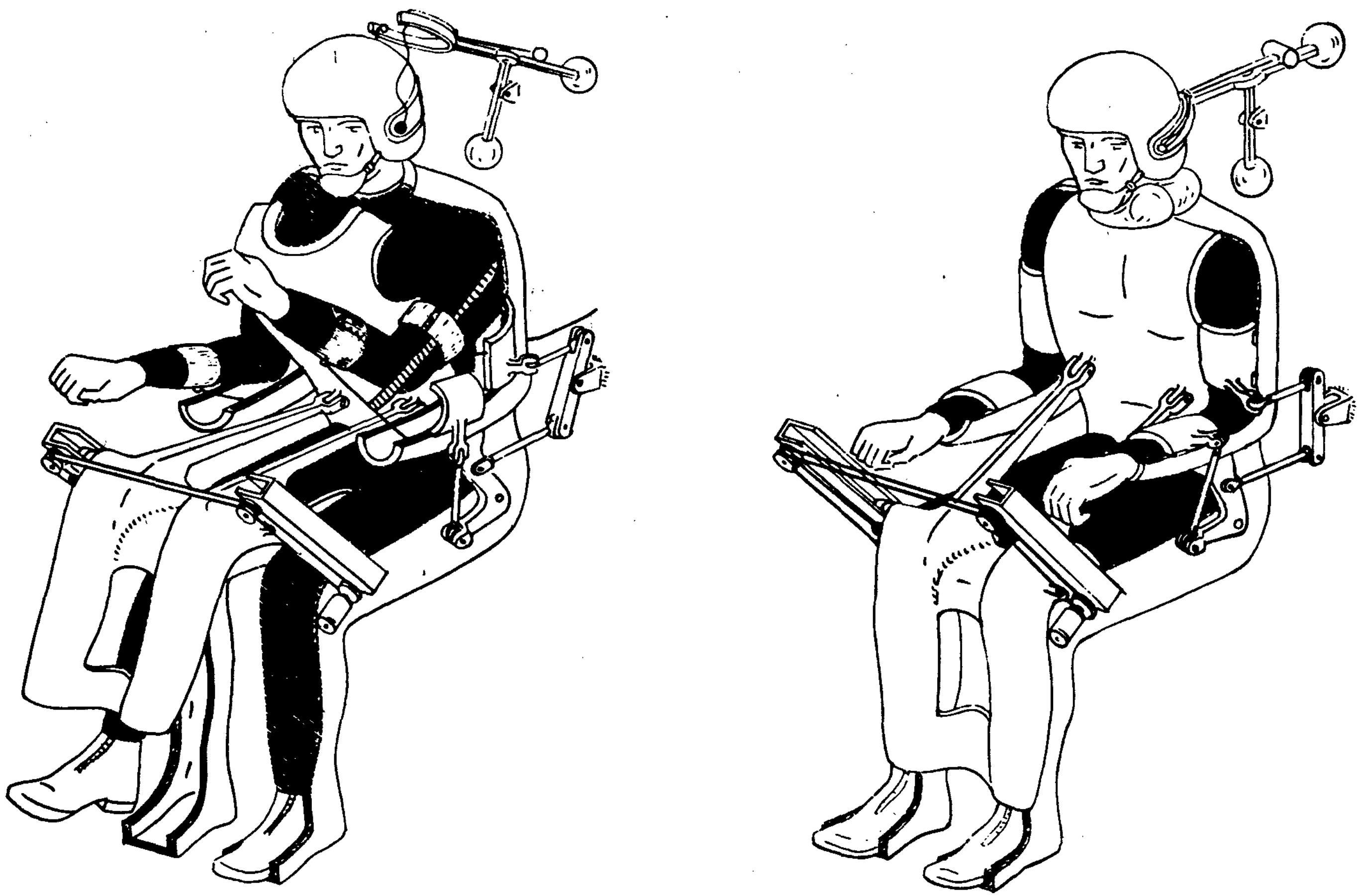
Head restraint is provided by an individually fitted hard helmet with firm interior padding. A chin strap prevents the head from submarining out of the helmet. The helmet is pulled by cables into a supporting yoke prior to the onset of accelerations. The yoke contains counterweights and turning joints to permit counterbalancing in three degrees of freedom for limited movements. With this system, the head can be wholly or partially supported in all directions and still be free to follow body movement. If partial support is used, a breakout device will be employed to hold the head rigid for extended period moderate accelerations.

Arm restraint is not illustrated in Figure 10 except for the half-zipper shown. The principle employed is to position the arm by zipping the half-zipper on the arm to a half-zipper on the armrest. This technique leaves the arms unencumbered and provides positioning by starting with the shoulder joint and camming the arm into position. A special zipper or a closure device followed by a standard zipper is required. After the arm is zipped to the armrest, protection is similar to that of System 2.

Leg restraint is provided by a strap system integrated with the suit and a hard shell behind the calf. A strap type of cup over the knee is pulled back to a point under the seat to hold the knee down and back. The grounding point is close to the knee to minimize strap stretch. Straps above and below the knee cup are adjustable to position the cup. Calf restraint is provided by two broad straps that hold the calf to the hard shell and a cable that retracts the shell against a rest. The calf retraction cable is normally stowed by going vertically to the knee joint and back to the retraction drum to remove all restriction from the calf. A broad band under the upper thighs is squeezed against the thighs by the automatic lacing principle and strapped down to the seat. This device provides vertical and lateral thigh tiedown and reinforces the pelvic joint for knee antisubmarining. A microballoon bag or water-saturated polyurethane-sponge LIQUIFOAM is used for a contoured seat cushion.

4. Seat-mounted Clamshell Restraint System (Figure 11)

This system is designed to provide maximum protection and mobility for a man in a flight system not requiring crew rotation. The seat is a Mercury couch molded to fit the posterior portions of



NORMAL

FULL RESTRAINT

FIGURE 11 CLAMSHELL CONCEPT

the man except for the head. A thin polyurethane padding covers the couch surface. The crewman enters the vehicle wearing a nylon flight suit, high-top shoes, a sacroilliac corset and seat belt, and a form-fitted helmet. He must disconnect the anterior shell at the pelvic attach point and slide into the seat. He buckles his seat belt and attaches positioning cables to his upper and lower arms with small cuffs. The anterior thorax shell is then connected at the pelvic attach point. The anterior shells consist of a thorax shell pivoted at the pelvic joint and a thigh and leg shell attached to a slide mechanism at the knee and to the thorax shell. In addition, two shells on each arm clamp the arm after positioning. For normal flight, the anterior thorax shell rotates forward permitting the man limited forward torso movement, relieving him of pressure and providing ventilation. The leg shells are raised, permitting free movement of the legs and thighs within limits. When the automatic system is initiated, the thorax shell rotates back, camming the torso into position and restraining it in a hard shell. The leg shell cams the thighs and calves into position and restrains them, including knee antisubmarining.

Head positioning is accomplished by inflating formed pads on the anterior and posterior shells. A moment balance device, similar to the one in System 3, is directed into sockets on the helmet by a power system and automatically locked into place.

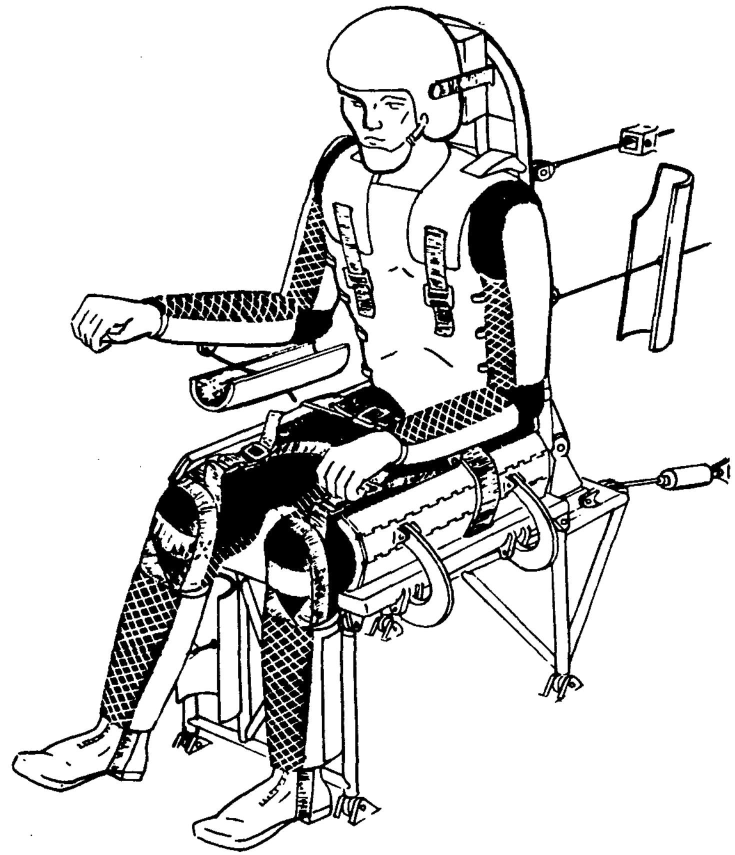
5. Hard-shell Restraint System (Figure 12)

The objective of this restraint system is to provide the crewman with the maximum of physiological protection while preserving as much mobility as possible and permitting crew station rotation. The concept is predicated on the premise that the crewman's lightweight, rigid-torso shell also forms a portable, pivoting seat back. This device, which is fitted to the individual, has a structural frame integrated into the posterior shell similar to a woodsman's pack. The back frame carries an integral headrest, as well as having structural attachment points. This torso garment is worn by the crewman when transferring from station to station, or may be easily removed during rest periods.

Proper tooling of the structural attachment points allows each crewman to engage his seat back with the crew station seats which are adjustable to accommodate all percentile sizes. A manual control handle enables the crewman to engage and disengage himself from the seat. Once seated, floating pivot points allow the crewman to bend forward at the waist. Since his restraint moves with him at all times, the crewman never leaves a proper relative position. Extendable shoulder retraction cables, operating in conjunction with a locking device at the seat pivot, immobilize the seat back upon application of restraints.

The rigid-torso shells provide maximum protection for the thorax and abdomen by preserving the natural shape of the body under loads and preventing distention of the soft tissues. When used in conjunction with the integrated foundation garment (Figure 13) excursion of the internal organs is sharply reduced.

CREWMAN BETWEEN STATIONS



SEATED CREWMAN

FIGURE 12 HARD-SHELL CONCEPT

A liner is integrated in this concept which provides comfort padding and permits limited variation of body sizes within a given shell. This liner, LIQUIFOAM, consisting of an open-celled foam sponge within a flexible sheath, is capable of being saturated with fluid. By excluding the air from the liner, the padding becomes relatively incompressible if the fluid is trapped and slightly pressurized upon actuation of restraint. At the same time, pressurization causes the liner to expand inward around the body to form a self-contouring load-carrying pad. While some redistribution of fluid occurs during application of loads, the cellular structure of the frame acts as a damper, restricting the flow. Furthermore, the capillary action of the sponge prevents sloshing or pooling of the fluid. Upon relaxation of the restraint, some fluid is released from the liner, allowing it to contract away from the body and restoring its comfort padding characteristics. If a satisfactory means can be devised for injection of microballoons, these lightweight spheres might be utilized in this application to achieve a saving of weight.

Semicircular shells, employing similar liners, are used on the back of the arms and lower legs. Reinforced fabric around the front of the limbs, which gives broad load distribution, can be integrated into the flight suit. The hard shells on the limbs help reduce distortion of the members under acceleration, provide a single point attachment for retraction, and protect the limbs from injury during rapid retraction into the restraint cradles. An attempt will be made to integrate the fluid connections with the cable attachments or with those of the torso-shell liner in order to minimize the number of connections.

Supplementing the hard-shell restraint of the legs is a knee harness which restrains the knees downward and aft in the seat to prevent submarining. This harness, in conjunction with the pelvic belt in the integrated foundation garment, stabilizes the pelvis by furnishing an axial reaction through the thigh. This harness may also be integrated into the flight suit. The knee hold-down strap, which runs under the heel, may also be utilized for foot restraint.

The seat employed with this concept has adjustable thigh pads and a contoured support between the knees. The thigh pads, which are articulated to accommodate all crewman sizes, are lined with fluid-filled foam pads as is the seating surface. After the thigh belt is adjusted to position these pads for the individual crewman, pressurization of the pads tightens the restraint, thus supporting the hips and compressing the buttocks.

The illustration shows an operational version of the seat, articulated to allow optimum orientation for cruise or launch. For the test program, this seat could be greatly simplified with bolted adjustment provisions, since adjustment during the test would not be required.

The integral head restraint illustrated with this concept employs two helmet straps which can be tightened to hold the head in a deeply contoured headrest. Lateral and transverse restraint is thus achieved, while limited vertical head motion is allowed.

For added comfort, ventilation of the underwear may be desirable.

6. Integrated Foundation Garment (Figure 13)

A multi-purpose, heavy-duty undergarment is proposed for restraint of the abdomen and the genitals. This garment which resembles a medical abdominal girdle, incorporates sacro-lumbar contour formers, as well as a heavy-duty athletic supporter. It also has provisions for removable athletic-type pads to protect against inguinal herniation. Integral with the garment is a pelvic belt, which distributes hold-down and hold-back loads across the crests of the ilium. These points furnish two of the relatively few hard points of the body which can be positively restrained. By restraint at these points, plus knee support to provide stabilization of the rolling moment imposed upon the pelvis during submarining, alignment of the lumbar area of the spine can be maintained.

Light weight stays on the front of the garment assist in preventing distention of the abdomen. Additional abdominal protection may be obtained by means of an inflatable bladder which provides local constriction of the abdomen.

Provisions may also be readily made for a protective metal cup. While the molded torso shells probably do not require this feature, with systems which employ crotch straps or harness hold-down straps for this area, it may be necessary. If this be the case, provisions for removal of the cup to facilitate relief of the bladder are easily provided. Use of such a cup should be avoided whenever possible due to the discomfort, particularly when seated for long period of time.

Zipper closures on the garment are provided on each leg for donning.

This garment may be utilized in one of several possible versions with all of the restraint concepts proposed. Its ability to stabilize the sacro-lumbar area of the spine, as well as to control distention of the lower abdomen is well known by those who have had to wear this type of orthopedic appliance. By virtue of its design, distribution of the belt loads across the pelvic crests can be assured. Its comfort for long periods of time may be questionable, although means may possibly be devised (such as inflatable bladders) to tighten or relax its restraint as needed.

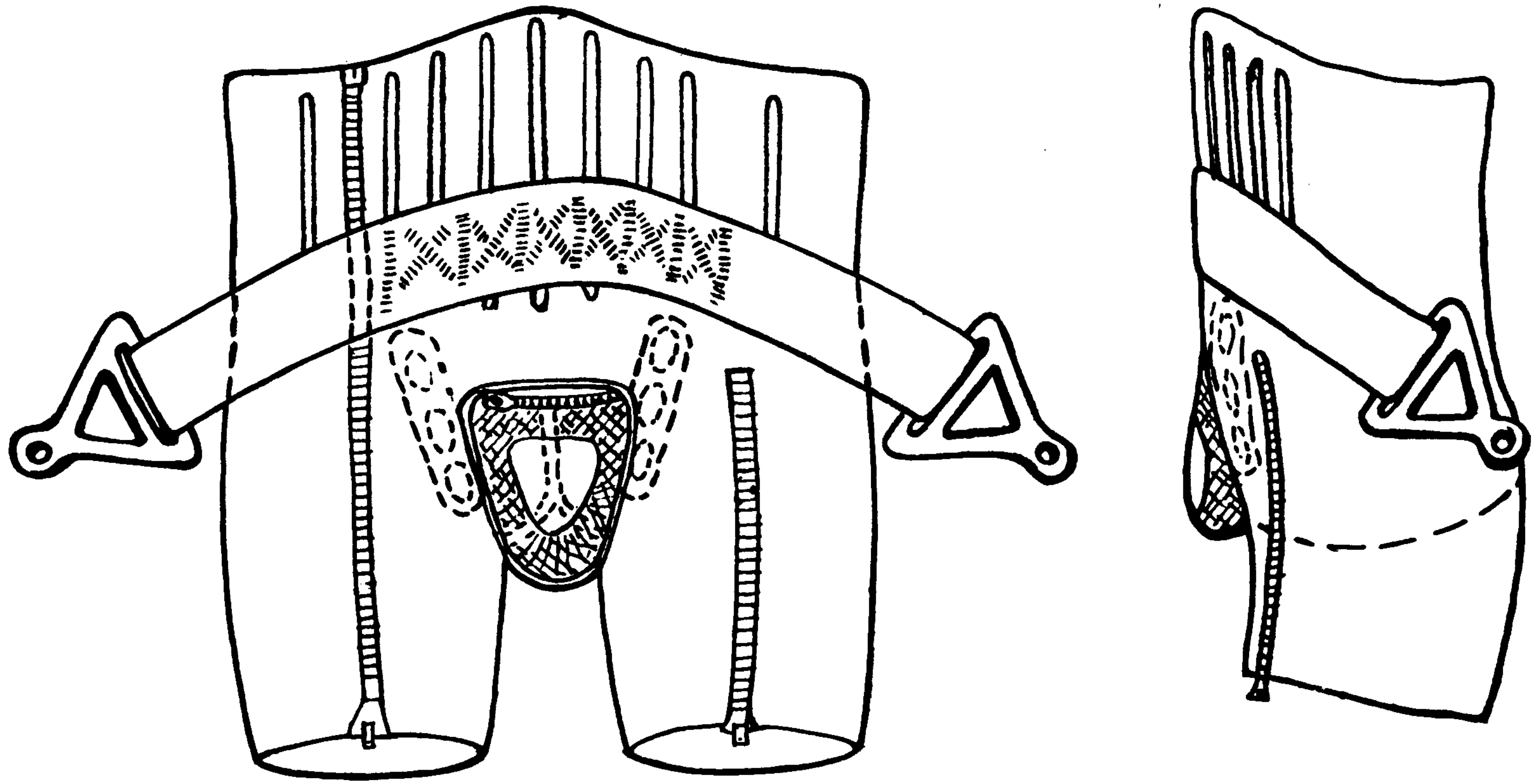


FIGURE 13 CONCEPTUAL INTEGRATED FOUNDATION GARMENT

D. Concept Evaluation and Selection

A team of crew equipment designers, medical specialists, and experimental pilots evaluated the concepts. Some of the evaluators had participated in the conceptual portion of the program and some had no previous program background. Evaluation was made by restraint-support element to assure that each detail concept would be evaluated on its own merits. Votes were taken to systemize the procedure; however, the numerical results are significant in a relative sense as they represent a function of arbitrary weighting factors only. The weighting factors used placed heavy emphasis on the protection potential of the concept.

Scores and comments resulting from the evaluation were studied and an over-all system of compatible element systems was assembled for presentation to AMRL. The recommended system concept is illustrated in Figure 14. This system was somewhat less conservative than would have been selected by a simple tabulation of votes, reflecting the customary conservatism of group opinion. Elements of the system are described and the reasons for selection are given in the following paragraphs:

1. Torso--The mobile hard-shell seatback developed in System 5 was recommended for optimum torso protection. The evaluation team indicated an overwhelming preference for the two molded-body shell systems, 4 and 5, on the basis of maximum protection. Rigid, form-fitting encasement of the thorax and abdomen appears to offer far greater protection for body structure and internal organs than any of the soft body-restraint systems. The soft systems, due to their flexibility, allow distortion of the thorax and distention of the abdomen permitting greater excursions of the soft viscera. Rigid torso shells also require fewer attachments as the loads can be distributed within the rigid-shell structure. The primary disadvantage of the rigid torso shell is the requirement for selective fit. This disadvantage may be partly alleviated by using a range of finite sizes and expandable liners. The liners might be used to tighten the torso in the shell before impact. If the liner expansion is reversible, adding water or microballoons for example, it would be possible to tighten and relax restraint in flight.

It should be noted that the protection afforded by the clamshell and hard-shell is identical when under full restraint. The hard-shell was chosen because it allowed more continuous protection and was adaptable to multi-place flight systems.

2. Head--The soft head-restraint from System 2 was chosen to permit larger head excursions than the rigidly encased torso to allow following of the torso on impact. This concept was chosen over moment balance of the helmeted head, as described in Systems 3 and 4, on the basis of simplicity and comfort in an environment that does not require the foreign object protection of a hard helmet. Dacron webbing, positioned and retained by a soft helmet, restrained most of

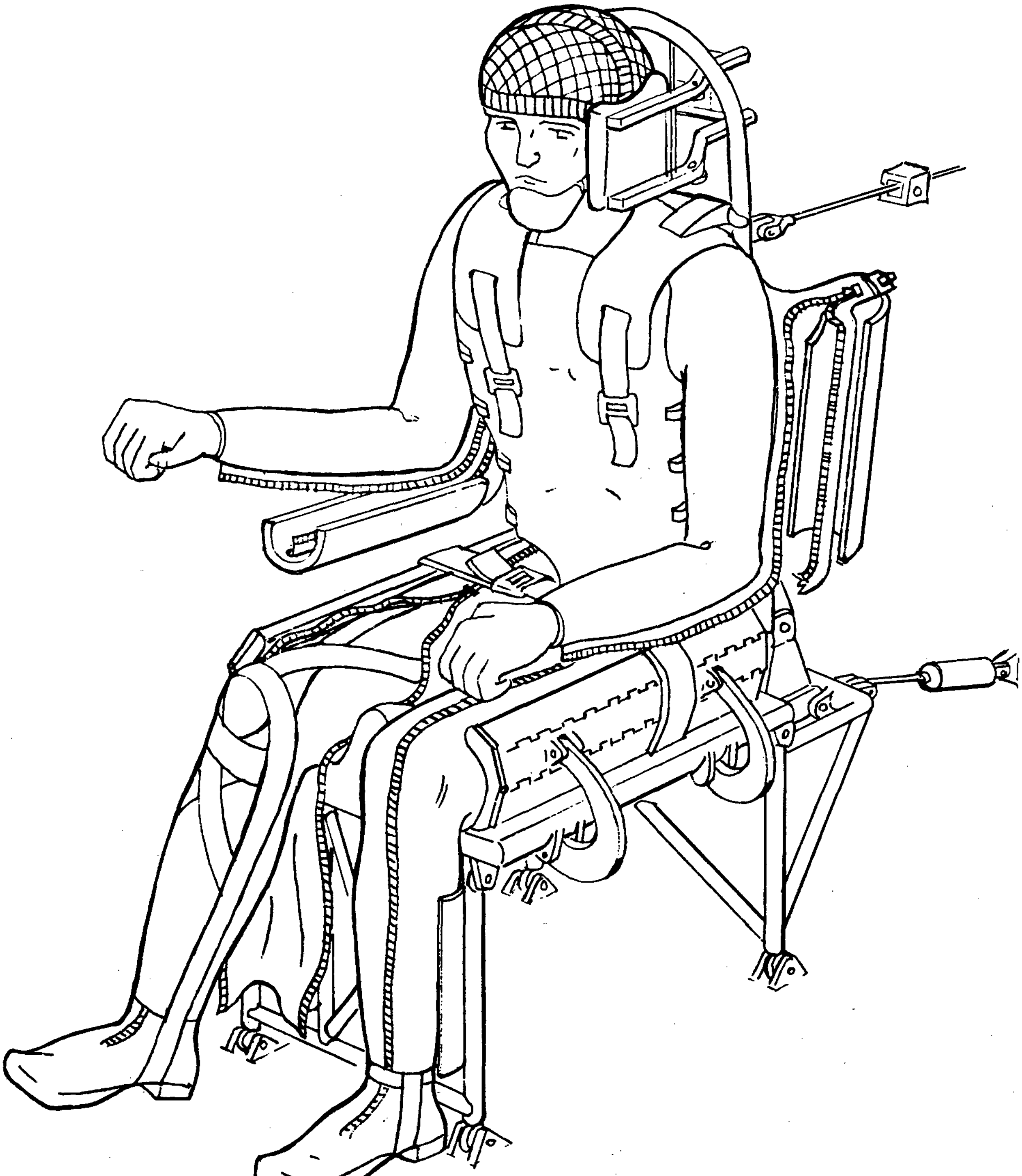


FIGURE 14 RECOMMENDED RESTRAINT SYSTEM

the head's $-G_x$ inertial loads by bearing on the forehead. Additional straps stabilize the head through a padded chin cup. The $+G_x$ loads are restrained by the headrest bearing on the occipital bone at the back of the head.

The $\pm G_z$ loads are carried by the neck, as these loads are at approximate right angles to the retaining straps. Based on unpublished ejection-seat test data, it was concluded that the head was marginally able to withstand the $+30G_z$ impact if it was not burdened with a hard helmet (i.e., three to five additional pounds weight). Virtually no data exists on human $-G_z$ tolerance in excess of 10G. It was postulated on the basis of animal tests (Reference 29) that the head was marginally able to withstand $-20G_z$ without vertical support (and without the additional weight of a hard helmet). If the environment should require a hard helmet, full or partial moment balance similar to Systems 3 and 4 will be required. One significant anatomical fact was clearly brought out in the skeletal study of the head and torso and is reflected in the decision to permit vertical head movement. The spine is virtually a constant stress or graduated cross-section column designed for $+G_z$ loads. The inertial load of the torso cannot be supported by the upper extremities of the spine for significant acceleration loads.

Lateral head support is provided by broad, rigidly mounted pads surrounding the ears. These rigid pads would not have been recommended if rigid torso restraint had not been chosen. All soft torso restraint systems studied or developed on this program would permit large lateral torso excursions on impact.

3. Limbs--Zipper arm positioning and restraint was recommended because it provided a satisfactory level of restraint with minimum encumbrance to the unrestricted arm. It was recognized that a zipper would have to be produced or developed that would pull the two halves together with greater force and more reliability than current zippers. The development was considered justified by the complete absence of dragging cables or links on the arm and the completely safe, anatomically compatible mechanism of arm positioning made possible by the concept. Positioning and restraint is accomplished by zipping a flap on the sleeve to a flap on the armrest. The zipper is started at the shoulder and directs the arm into the armrest until it reaches the wrist. A tensioning device can then tension the retaining flap.

Legs are positioned and prevented from flailing by a zippered tube system, starting at the upper thigh and working down to the ankles. Full mobility of the unrestrained legs is assured and toe-pedal operation by the crewman is possible under full restraint. Antisubmarining protection is provided by a knee strap system with attachment points at the seat back, thereby permitting full leg mobility. The strap system supports the thighs and lower pelvic girdle during $-G_x$ accelerations by restraining the femur through the patella. Upward loads in the knee restraint tiedown straps under the arch of the shoe, generated by tension in the tieback straps at the moment of impact, are reacted into the zippered tube.

4. Seating--The universal seat pan from System 5 was recommended. A flat sitting-surface covered with LIQUIFOAM and multiple-hinged lateral-support pads lined with LIQUIFOAM and retained and adjusted with a lap belt provide support for the buttocks and thighs. The LIQUIFOAM sitting-surface is comfortable for normal operation, but presents a hard contoured surface at impact to relieve the load on the ischial tuberosities. Lateral pads support the thighs and lower torso under G_y loads and reinforce the hip socket under antisubmarining loads. Thigh inertia under $-G_z$ loads is retained by the lap belt and upper portion of the lateral support pads. Thigh support under $-G_z$ loading is a vital consideration in reducing the loads on the spine as the torso loads up the shoulders and the small end of the spine. The seat also serves as support for the torso hard-shell pivot and as a means of changing crew orientation for physiological protection from sustained accelerations.

5. Foundation Garment--A foundation garment similar to Figure 13, but without seat belt, was recommended for protection of the torso area below the torso hard-shell trimline.

E. Philosophy of Selection

From the foregoing discussion and from Figure 14 it is obvious that the system recommended is a conceptual research configuration. It was not intended to fit any specific vehicles, class of vehicles or specific test equipment. It was not the product of an attempt to dogmatically expand a single basic concept into an over-all system design. The recommended system reflects the purpose of the initial phase of this program: to develop new concepts in personnel restraint that will increase personnel protection from impact accelerations and to present the conceptual system to AMRL for selection of a test configuration. Increased protection was the primary objective, with operational feasibility as a constant consideration. The recommended system is not an operational prototype; however, all concepts inherent in the system are compatible with operational requirements.

SECTION VIII

TEST SYSTEM DESIGN AND FABRICATION

Results of the conceptual studies and recommendations for the test system were presented to the project staff at AMRL. The project staff was in general agreement with the recommended system concepts, but with some reservations on the operational feasibility of zipper positioning and the multiplicity of straps in the knee restraint harness. Discussions centered primarily on the design of a test system for manned testing of the basic principles. It was mutually agreed to delete zipper retraction on the test configuration, because of the zipper development required. Manually operated arm and calf covers were substituted. Integration of the torso hard-shell and seat back in the recommended system was designed to save weight and facilitate crew rotation. The universal, adjustable seat was also designed for crew rotation. Crew rotation was not a major consideration in tests with a small test panel. A tubular-steel seat frame, into which the test panel's torso and seat shells could be socketed, was chosen for the test configuration. Positioning and pretensioning systems were not designed or fabricated for the initial tests; however, the system hardware was designed to be compatible with future incorporation of these systems.

After the initial agreement, two changes were made to the test concept to more nearly approximate the basic concepts and to reduce encumbrance in the unrestrained condition. An arm retraction system utilizing a strap replaced the manual arm cover. This concept can be fully mechanized for the ultimate prepositioning and pretensioning demonstrations. A rigid cover for calf and knee restraint was substituted for both the knee restraint strap system and the manual calf covers. This system can be mechanized for future demonstrations. Both changes were approved by AMRL. The system approved for design and fabrication to test-prove the concepts is illustrated in Figure 15.

Fabrication of the system and its supporting test fixtures was divided between the government and the contractor. The government designed and fabricated the six-direction test fixture and fabricated the contractor-designed seat; laid up the basic fiberglass hard-shells to the test subjects' anatomies per contractor specifications, and performed the system dynamic proof tests. The contractor fabricated the head restraint system, headrest, armrests, legrest, leg cover, and auto-just and built up the GFE shells with structural support members, liners, and special hardware.

Detail design of the test system was initiated on the basis of an unmechanized-bolted-together system. It became immediately obvious that this approach was not safe for a manned test system because of the time required to extricate the test subject. Many of the items described below, such as the linkage on the lateral head

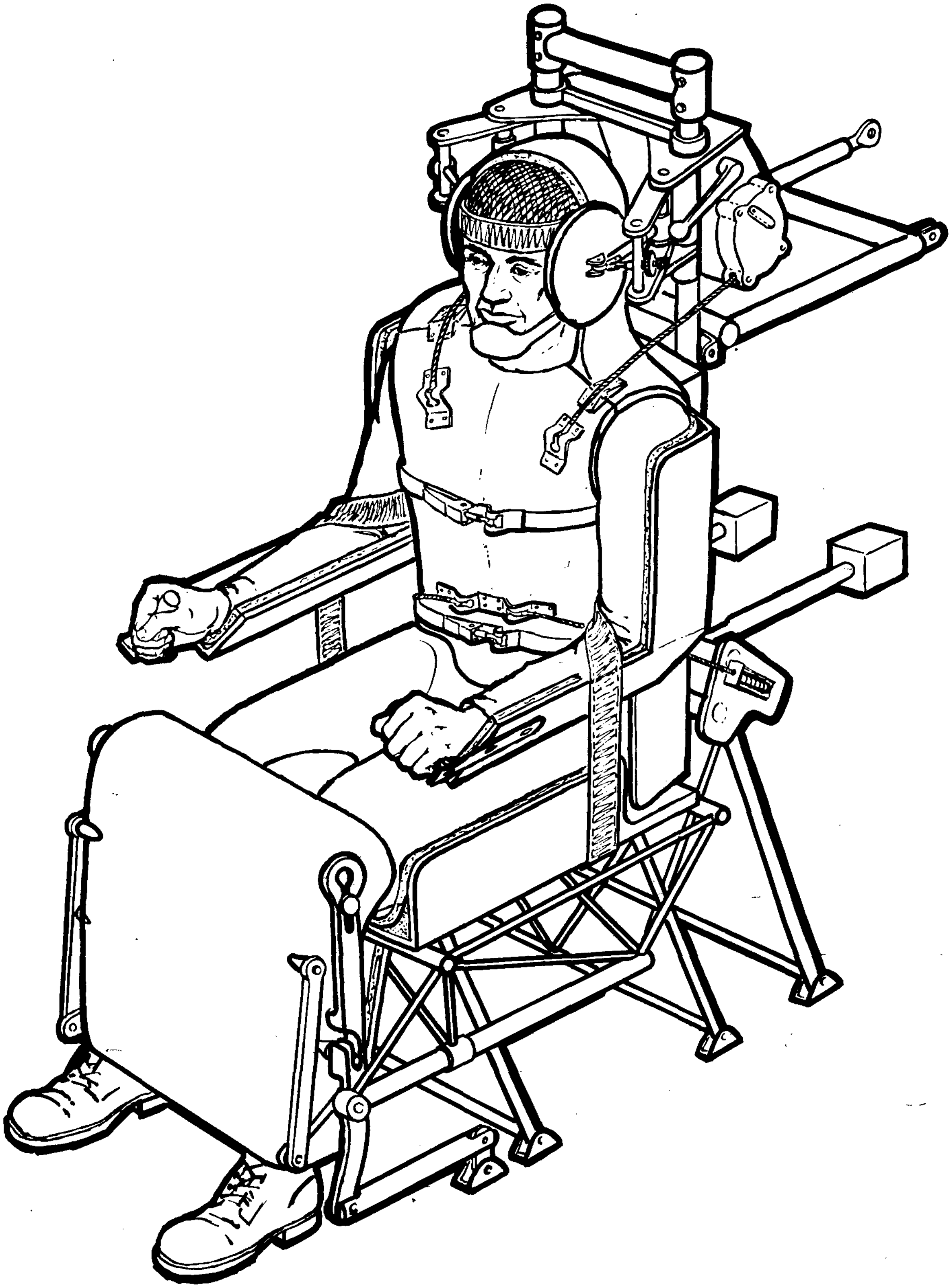


FIGURE 15 SYSTEM SELECTED FOR DEVELOPMENT

supports, leg cover mechanism, and auto-just were the result of this test safety requirement. Elements of the test system are described in the following paragraphs and illustrated in Figures 16, 17, 18, 19, 20, 21 and 22.

A. Test Fixture

Impact tests were conducted by the free-drop technique. Drop-test fixtures are normally heavy platforms on which the test items are mounted. For this test program it was desirable to drop in any of six directions. The multi-directional objective posed a number of problems. There are over-all practical weight limits for both the hoisting mechanism and the attenuation media used to program G-time exposures. Structural requirements are severe and cannot be alleviated simply by adding additional structural material as all such material adds to the inertial loads. Finally, the response characteristics of the drop fixture must not be such as to affect the actual acceleration incident on the man and his protection system or to blank out accelerometer readings.

A tubular-steel frame was fabricated for structural proof tests of the system with a 95-percentile anthropomorphic dummy as the test subject. This fixture has been successfully used to demonstrate structural integrity of the restraint-support system to 120% of anticipated loads using precalculated acceleration values based on drop height and attenuation stroke. Accelerometer readings are largely obscured by fixture vibration, making this fixture largely unsuitable for high G manned testing. A cast-aluminum platform on which the test system can be oriented, as required, is under study.

B. Test Seat

An articulated test seat with a tubular-steel frame, adjustable to two positions, was designed and fabricated. A torso-aft reclining position provides the customary comfort position for long-duration flight systems. A torso-forward position provides the generally accepted crew orientation for large forward-velocity changes such as boost and rearward-facing reentry. During the transition from one position to the other, the crewman rotates about a theoretical shoulder pivot permitting fixed armrests and hand controls. Also, his thighs rotate relative to his torso about a theoretical hip pivot which prevents the back scrubbing inherent in seats that pivot at the intersection of the seat back and seat pan. In addition to these operational features, seat motion is used for actuating many of the restraining devices described below and in Section IX. Full restraint is imposed in the torso-forward position, automatically applying full restraint during the parts of the mission most subject to stress. The seat is shown in five of the system illustrations. Figure 18 shows the seat in the full-restraint position.

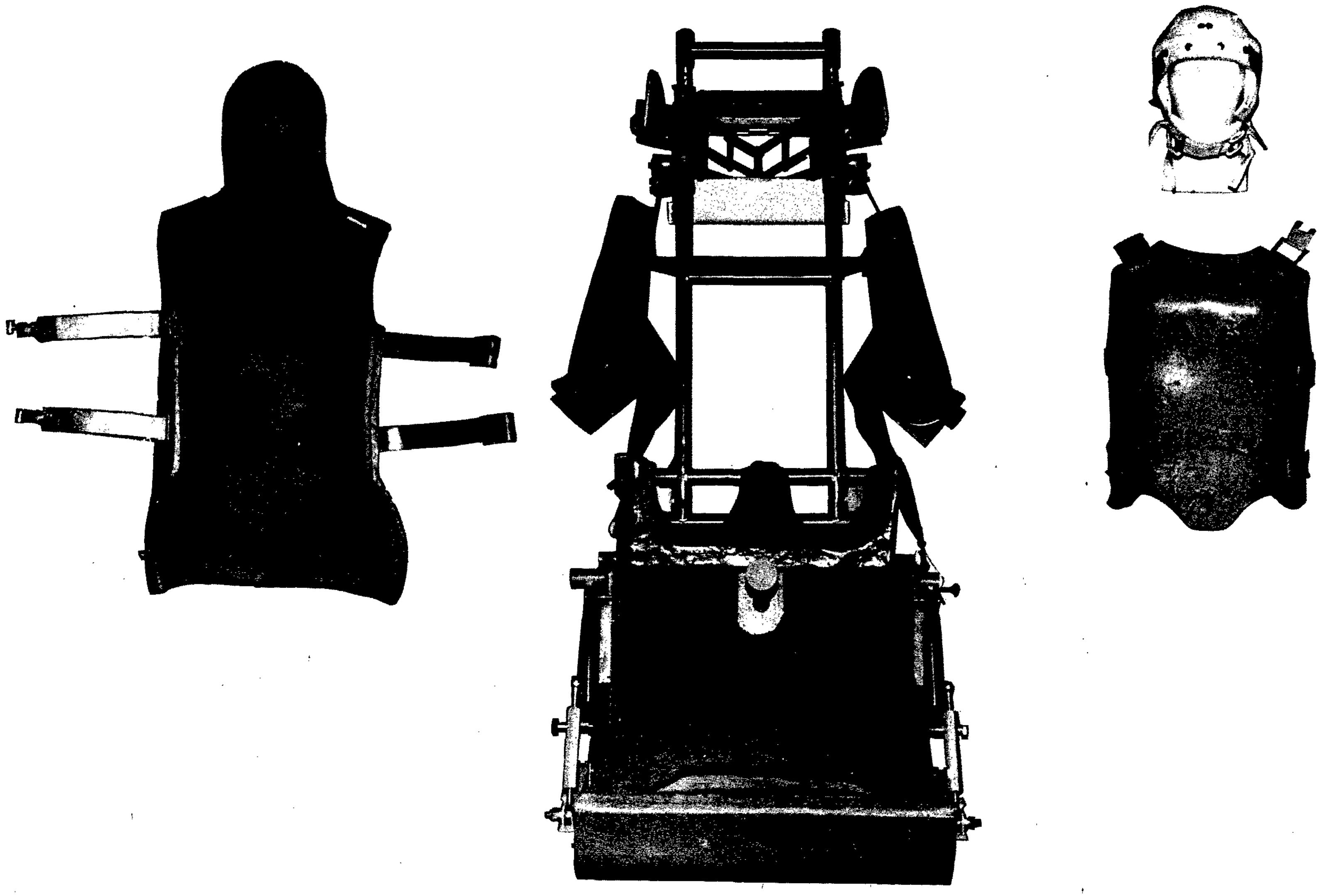


FIGURE 16 SYSTEM COMPONENTS

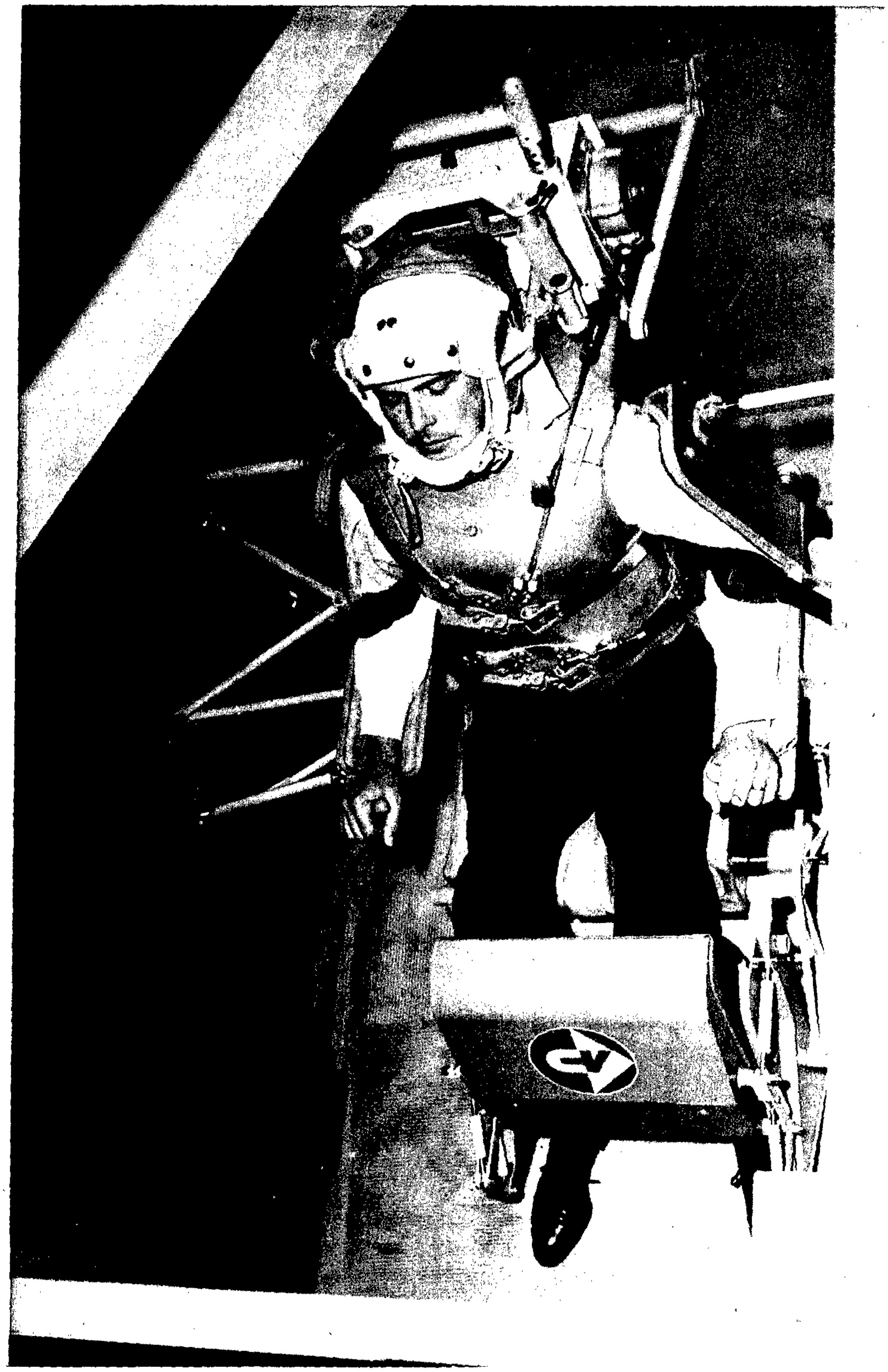


FIGURE 17 TOP VIEW OF SYSTEM

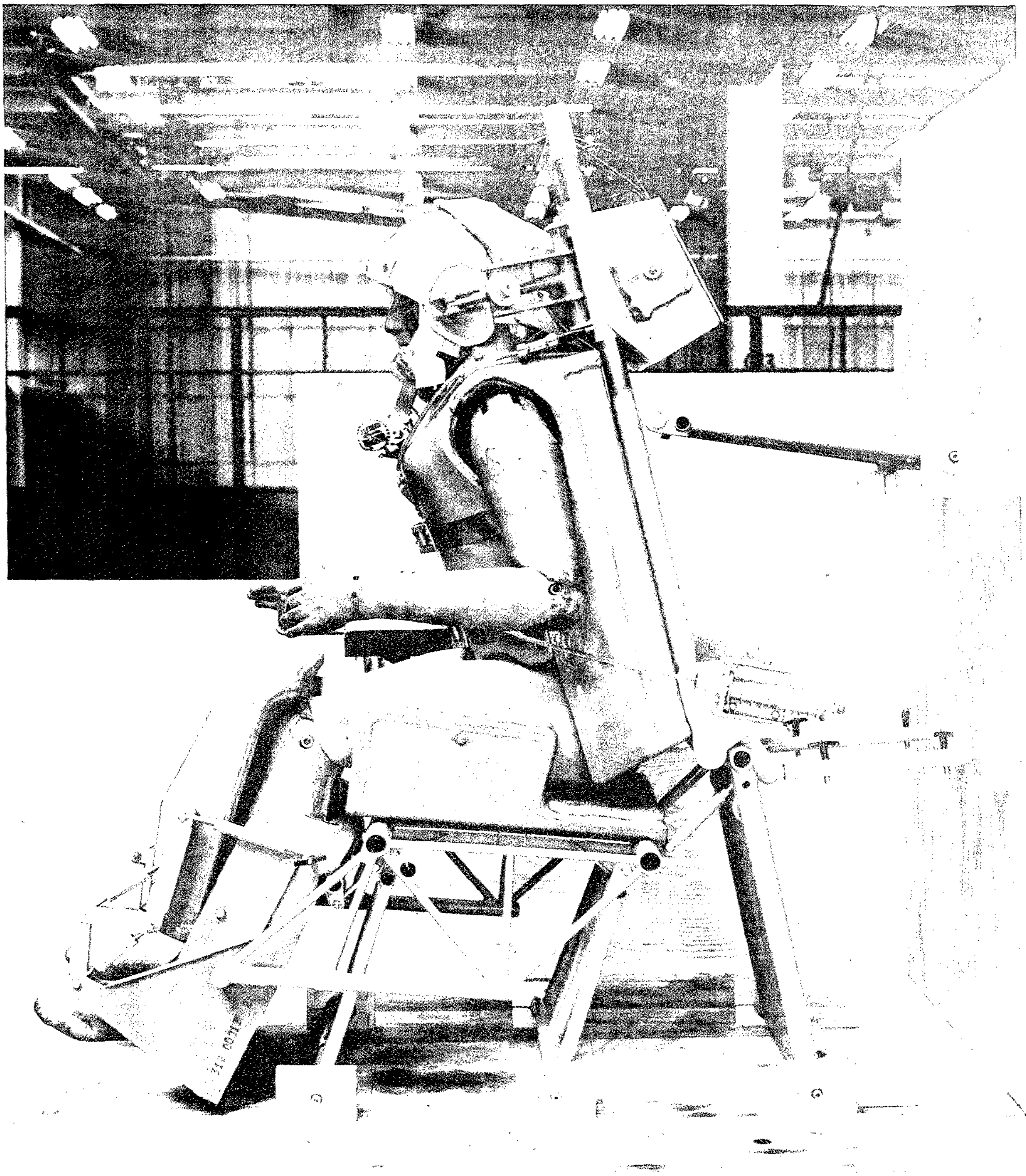


FIGURE 18 SIDE VIEW OF ANTHROPOMORPHIC DUMMY IN FULL-RESTRAINT POSITION

C. Torso Hard-shell

Basic fiberglass hard-shells were laminated by AMRL over plaster masters of the test subjects. A sand-casting process was developed to obtain the plaster masters. Both the contractor specification of the subject's posture and shell trim-lines and the casting process employed by the government proved to be major problem areas. Anthropometric variations in subjects percentile, variations within a percentile, and the absence of sharply defined reference points on the human body made specification of shells which were compatible with system attachments very difficult. Sand-molding proved equally difficult due to the flexibility of human flesh, posture characteristics, long term spinal disc compression, and movements due to breathing. Many of the casting problems were resolved when the technique was perfected to permit casting a subject in an hour or so total time.

Torso hard-shell assemblies were built up by fabricating a channel-shaped metal reinforcing member and bonding it to the fiberglass shells with foam-in-place plastic foam. This process provided an irregular sandwich construction to stiffen the hard-shell. A picture-frame type of shear member was built up from hat sections and riveted to the reinforcing channel. This frame fits into the tubular-steel seat back. An operational hard-shell would employ an integral ribbed fiberglass shell with a metal seat-back frame to accomplish the same mission with substantially less weight.

The inside of the initial shells was lined with LIQUIFOAM. This material was built up by coating the inside of the shells and one side of a half-inch-thick open-cell polyurethane-foam pattern with LP-2 sealant, and bonding the foam to the shell with the sealant. Sealant was applied to the exposed surfaces of the foam to completely enclose it except for two fill-ports. Finally, several coats of EC793 (a rubber-like structural coating applied as a liquid) were applied over the sealant. The assembly was evacuated, submerged, completely saturated with water, and the ports were sealed. The resulting padding was comfortable and easily contoured under slow compression loading, but hard and unyielding when struck a sharp blow. Later shells were lined with ensolite when the initial LIQUIFOAM liners experienced failures due to quality-control problems in the chemical processes. These problems could not be resolved within the scope of the program.

Special latches, locks, and shear fittings were developed to transmit loads between the torso breastplate and back-shell. Special retainers were built to retain the cables that hold the torso shell into the seat. All of the special fittings, except the two latches, had to be custom-fitted to the contour of each shell. These contours varied widely, producing a major problem in fitting steel hardware. The test torso hard-shell is shown on a subject as he would appear in transit between crew stations on Figure 19.

FIGURE 19 TORSO SHELL, SIDE VIEW

D. Seat Shell

Contoured fiberglass seat shells were laminated for the test subjects in a manner similar to the torso shells. Channel type reinforcing structure, foam formed in place, and picture frame shear fittings were installed. The seat shell was not intended to slip from the seat structure for mobility and was therefore retained by a hook at the back and a pin at the front. The pin is engaged and disengaged by a cable assembly. Seat shells provide a sitting surface and lateral support for the thighs. The sides of the shells forward of the torso shell are above the midline of the thighs. A raised center island supports the inside of the thighs. Initial shells were lined with LIQUIFOAM and later shells were lined with ensolite.

E. Head-Restraint

A dacron strap system supports the head under $-G_X$ loading. The straps are positioned by a leather helmet to assure a predetermined orientation. One strap passes over the forehead and terminates at the approximate head-neck center of gravity on each side. A second strap passes over the top of the head, through the CG, and is attached to both sides of an ensolite-padded chin cup. A third and fourth strap are sewed to the intersection of the first two straps and carry the head-restraint loads to structure. These straps are slanted downward to form a more direct load path with the forehead strap and route most of the load into the forehead. Annular ensolite pads around the ears are built into the helmet and ensolite padding is used under the forehead strap. Lateral head support is provided by pads that will be described in the next paragraph. A close-up of the head-restraint system is shown in Figure 20.

F. Headrest

A vertically adjustable carriage, mounted on the seat back, supports lateral head-support pads and harness reels for the shoulder cables. The lateral head-support pads are adjusted to fit over the ears by vertical adjustment of the headrest and adjustments on the linkage mechanism on which the pads are mounted. This linkage mechanism is an overcenter device locked by a quick disconnect pin to provide rapid egress. Proper vertical adjustment of the lateral head supports provides near optimum vertical adjustment of the shoulder harness cable reels. Note that the head is not supported by the headrest mechanism during $+G_X$ loads, but by the headrest integral with the torso hard-shell.

G. Auto-Just

Harness cables are used at the hips to hold the hard-shell back into the seat back socket. Conceptually these cables would be retained by spring-loaded harness reels. Harness reels with the required load capacity were not available and test safety precluded using a simple turnbuckle. A tensioning and locking device, using an interrupted screw,

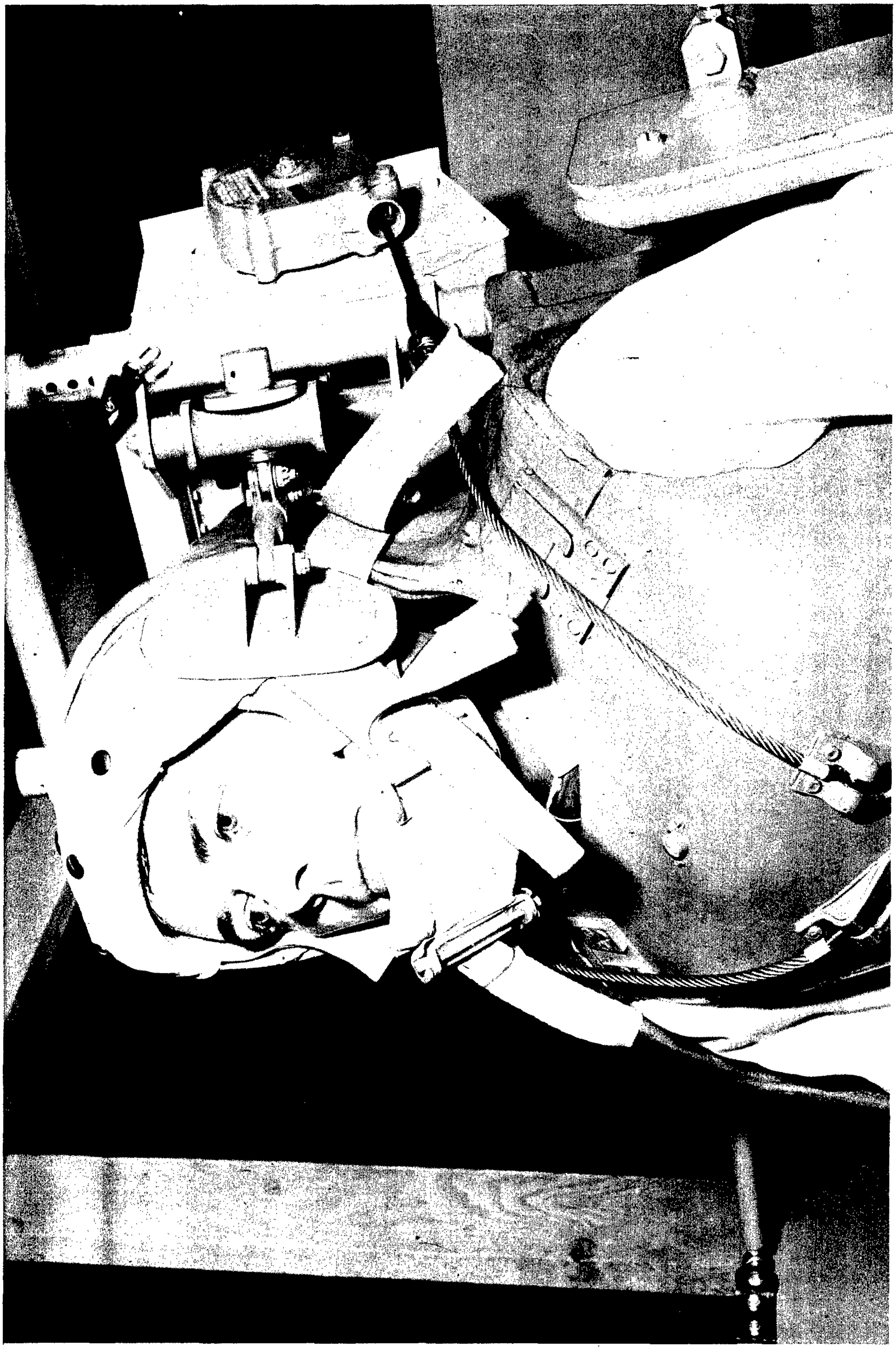


FIGURE 20 CLOSE-UP OF HEAD AND SHOULDER RESTRAINT

was designed to lock the cables at the desired length. The device, called an auto-just, is spring loaded and is shown on Figure 18.

H. Arm Restraint

Contoured armrests, mounted from the test rig structure, support the arms against $\pm G_y$, $+G_x$, and $+G_z$ loads. Hand loads and a broad strap over the elbow support the arms against $-G_x$ and $-G_z$ loads. The armrests are adjustable vertically and the upper portion is adjustable angularly for crew size variations. The armrests and arms remain fixed while the seat changes orientation. The strap system is anchored on the back side of the upper armrests, carried inboard over the elbow and attached to armrest structure. The armrests are lined with LIQUIFOAM. The armrest-and-strap system is illustrated in Figure 21.

I. Leg Restraint

Leg restraint is accomplished by two assemblies. A contoured leg backrest is pivoted on the seat frame and adjusted through a scissors assembly at the upper portion of the rest to position the upper edge against the back of the knees. A contact fit along the entire calf is assured by this means at the expense of fixing the leg rest angle for a given subject. A contoured leg cover pivots from the back rest and bears on the front of the calves and on the front and top of the knee. Two turnbuckles on each side adjust height and angle of the leg cover through a linkage and one turnbuckle on each side adjusts for the subject's calf thickness. Quick-release pins retain the latter turnbuckles to provide rapid egress. This leg cover is the test configuration of a concept in which linkages fold the cover down and back to direct the crewman's legs in place by a wiping motion during prepositioning. Both the leg rest and cover are lined with LIQUIFOAM. A center divider is produced by laying up the LIQUIFOAM over contoured ensolite. If the crewman's legs should be in an unusual position when the cover is actuated back the ensolite divider will not injure his legs.

J. Foundation Garment

Torso articulation requirements leave gaps in the rigid-shell torso protection. One such gap occurs forward of the torso-shell split line as it moves back from the side of the seat shell when the crewman is cycled to the full-restraint position. Another gap in the lower abdominal and inguinal areas is caused by the difficulty in fitting a rigid shell into such tight quarters. Still another gap is created by the back skirt of the torso shell leaving the seat as the subject leans forward. These gaps are bridged by the foundation garment illustrated in Figure 22. In addition to the customary hoop tension effect at the lower abdomen, the garment has a flap in front that tightens the upper thighs and buttocks area when the subject sits down and continues to tighten these areas as he leans forward. This garment is adjusted with laces in the customary manner but can be entered or left through zipper openings and hook fasteners. Note that a tight abdominal fit is neither required nor desired as it would loosen the crewman in his shell and permit him to gather relative velocity on impact.

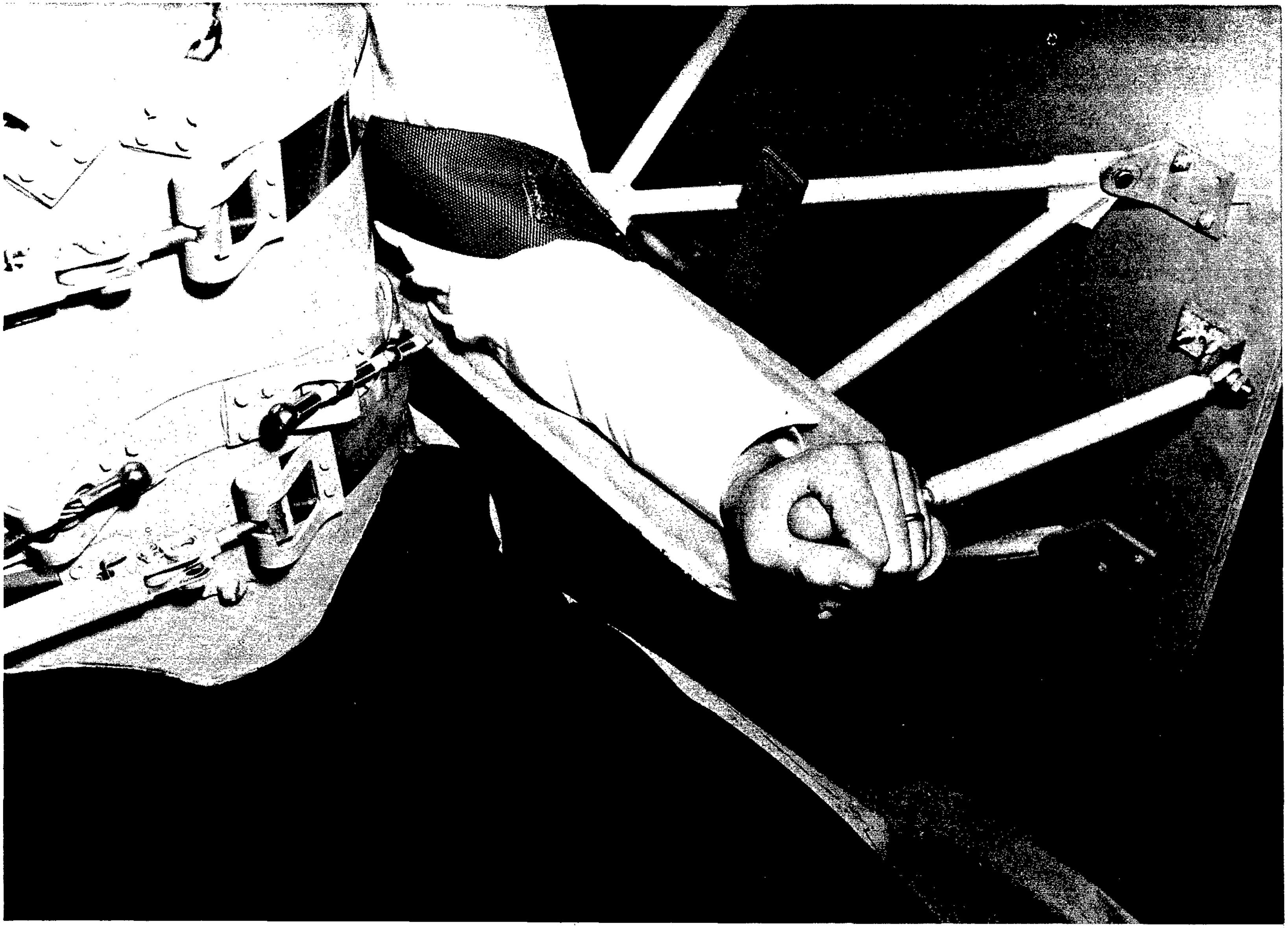


FIGURE 21 CLOSE-UP OF ARM RESTRAINT

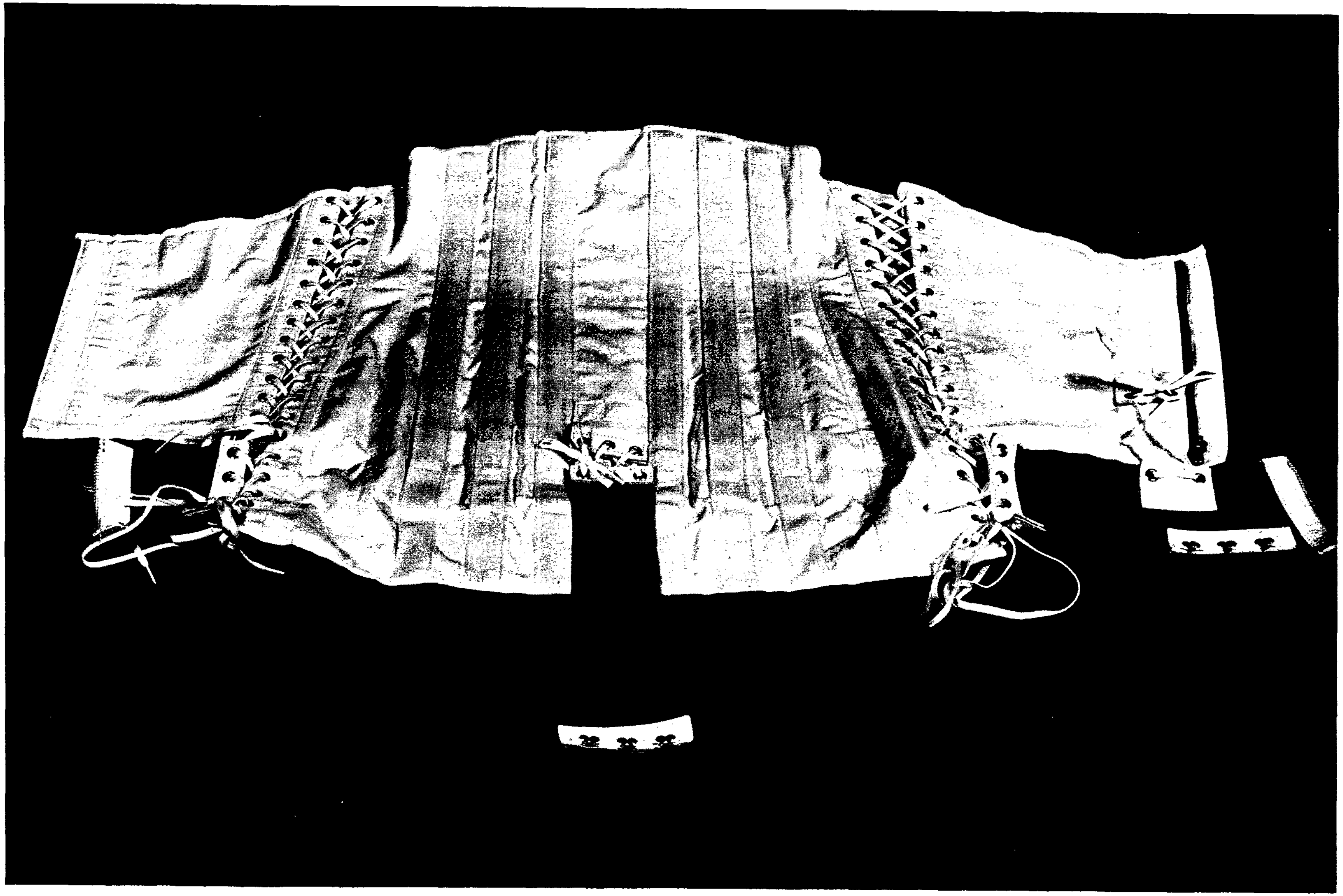


FIGURE 22 INTEGRATED FOUNDATION GARMENT

SECTION IX

PREPOSITIONING AND PRETENSIONING SYSTEM

Maximum crew protection from acceleration induced stress requires orientation of the crewman, application of restraining devices, and preloading of these devices to minimize body excursions relative to the restraint-support system. In subsonic aircraft with a fixed seat, lap belt, and shoulder straps, all of the above could be accomplished to the protection limits of the system by pulling four adjusting straps. Ejection requirements on supersonic aircraft were met with single-acting - ballistic and lanyard-operated systems that positioned the crewman for ejection, followed by ballistic releases for separation and parachute recovery. In spacecraft, the crewman will have a series of acceleration exposures with command functions during and after exposure. In addition, his required degree of protection will be higher, resulting in more changes and adjustments being made to effect the desired restraint-support. Mechanical systems that can be reversed and cycled repeatedly will be required to perform these functions if the crewman is to be free to control the mission. Mechanical, powered operation is also required to integrate the crew restraint-support system with the escape, abort, and warning systems.

Both conceptual design and test hardware for this program were directed toward providing restraint-support systems that were suited to prepositioning the crewman and his protective equipment and to pretensioning of restraint gear. A design for adding this capability to the test system was completed and submitted to AMRL for future fabrication. The designs and their conceptual operational counterpart are described in the following paragraphs. Note that the portions of the test system that affect body motions and the restraining member that contacts the body are in most cases identical for the test and conceptual operational systems.

A. Torso positioning requires pulling the torso back into a predetermined location and alignment. In the conceptual system the floating hip pivot would cycle to the closed position while the seat pan translated to the aft position. This would establish and retain the seat-back hard-shell pivot at the correct point. The shoulder pull-back cables would then retract the integral seat back into sockets on vehicle structure. By mechanically reversing the process, the crewman would be given mobility.

Torso positioning is accomplished in the test system by retracting spring-driven harness reels at the shoulders and hips which pull the torso-shell assembly into the seat back socket. When the hard-shell is firmly socketed, a sequencing switch is depressed and the seat cycles to the torso-forward-leaning position. The spring load pulls the hard-shell firmly against the seat and mechanical locks retain it. Test system reels are adapted from ejection-seat hardware and must be reset after each cycle. Forward positioning of the torso during seat cycling tightens the abdominal area in the hard-shell and foundation garment and causes the head to fall back naturally in the headrest to maintain visual contact with the instrument panel. Conversely, cycling back to the torso-aft position causes the head to leave the headrest naturally, providing free movement of the head. The torso pullback system for the test demonstration is illustrated in Figure 23.

B. Head Retraction

In the conceptual system the head would probably be retracted into the hard-shell headrest by light-duty power reels mounted on the hard-shell. Head retraction in the test system (Figure 24) is powered by the relative motion between the seat back and the upper back truss during seat cycling. Straps from the head harness are attached to cables which are routed down the back of the hard-shell to a trolley arrangement. A strut is attached to the seat-support truss and a trolley on the seat back. Cycling the seat from the torso-aft to torso-forward position drives a hook on the seat trolley from full up to full down. This hook contacts a bumper on the hard-shell trolley and forces it down, retracting the head. When the seat is cycled back to the torso-aft position, the hook leaves the bumper. The subject can then move his head forward until the hard-shell trolley is detented into the full up position and the head straps will remain slack.

On the conceptual system, the head lateral support pads would be mounted to vehicle structure and closed by an independent actuator as the last part of the prepositioning cycle. On the test system the angular relationship change between the seat back and upper back truss was used to power the pads. A parallelogram mechanism is utilized to transmit angular change since it is sensitive to angular change only and is therefore not affected by the 4-1/2 inches of headrest adjustment required to position the pads for all percentiles. The locking mechanism is similar to the unmechanized system with the primary structural links going over center to unload the parallelogram linkage. This linkage is illustrated in Figure 25.

C. Arm Retraction

Arm retraction in the zipper conceptual system would be actuated by a cable-driven trolley driving the zipper slide. For most environmental requirements, a strap system similar to the restraint portion of the test system would be adequate. It would be actuated by a harness reel pulling the slack out of the strap with a light spring-return device holding the strap up out of the way when restraint is not required. The crewman would have an override control he could reach when fully restrained so that he could unlock the reels and force his arms free if the system malfunctioned in full restraint. The test system, illustrated in Figure 26, is based on this concept except that the slack is taken out of the straps by a pulley-line shaft system driven by seat motion. Existing harness reels did not provide

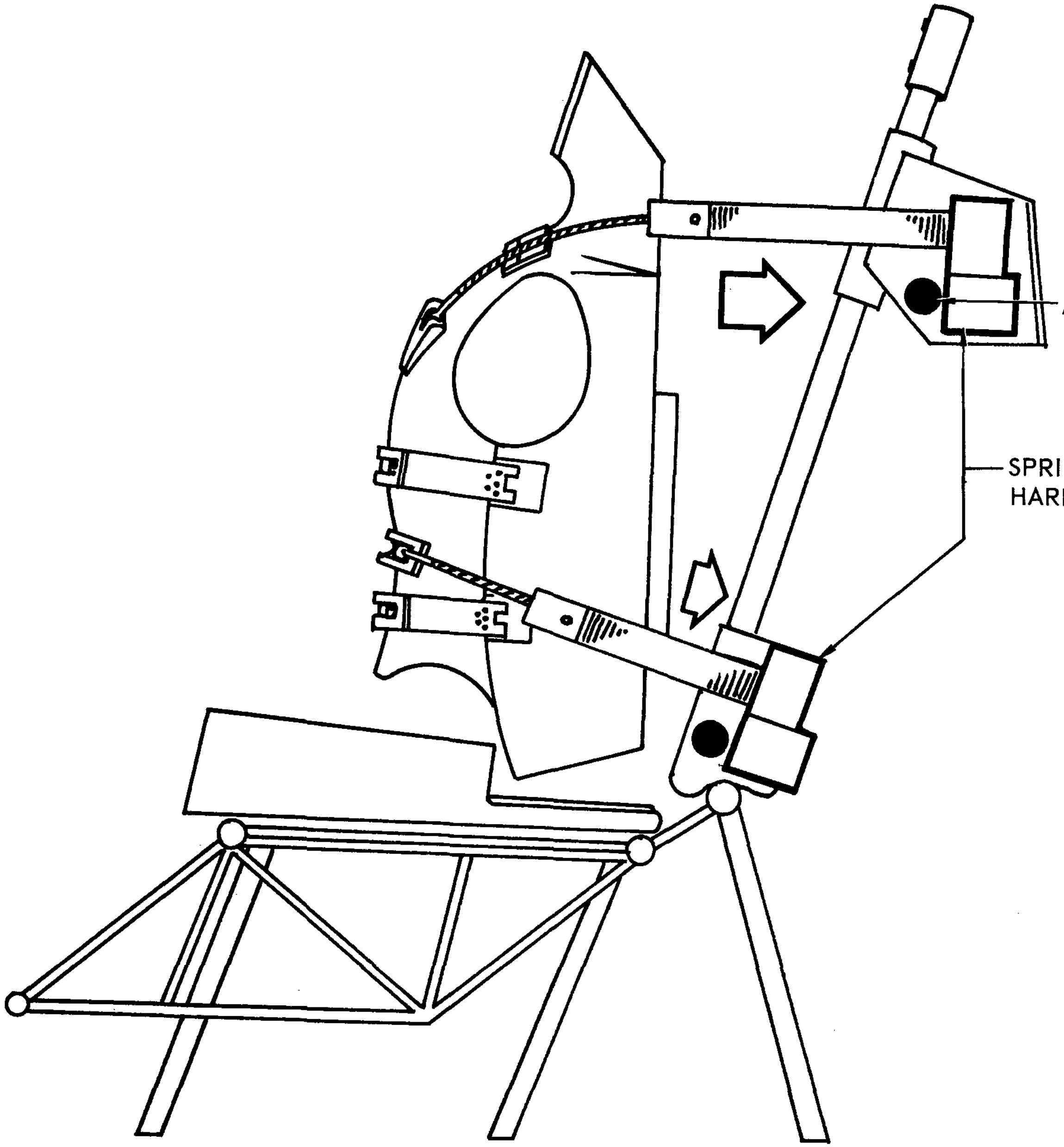


FIGURE 23 TORSO SHELL RETRACTION SYSTEM

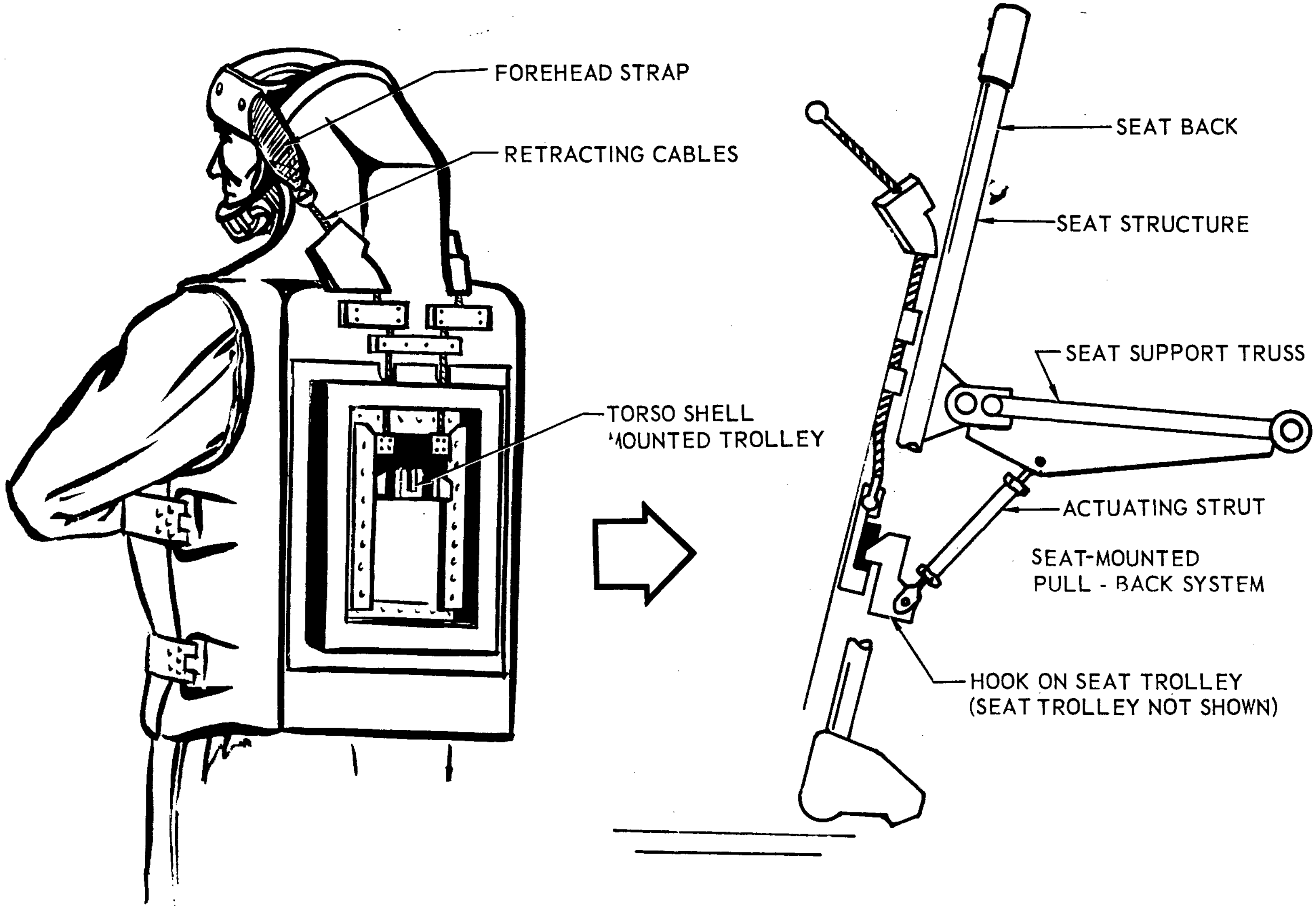


FIGURE 24 HEAD RETRACTION SYSTEM

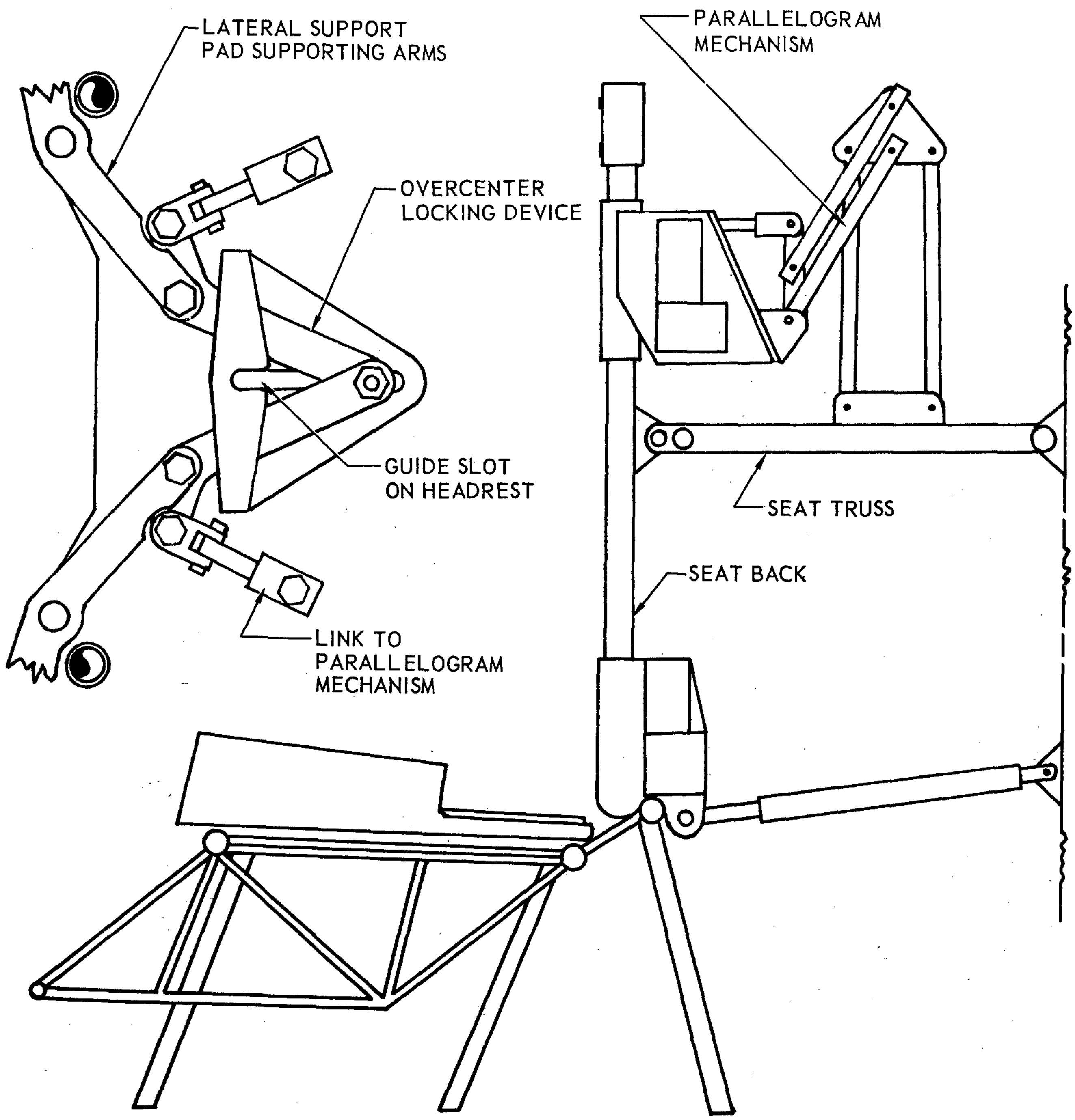


FIGURE 25 HEAD LATERAL SUPPORT ACTUATION

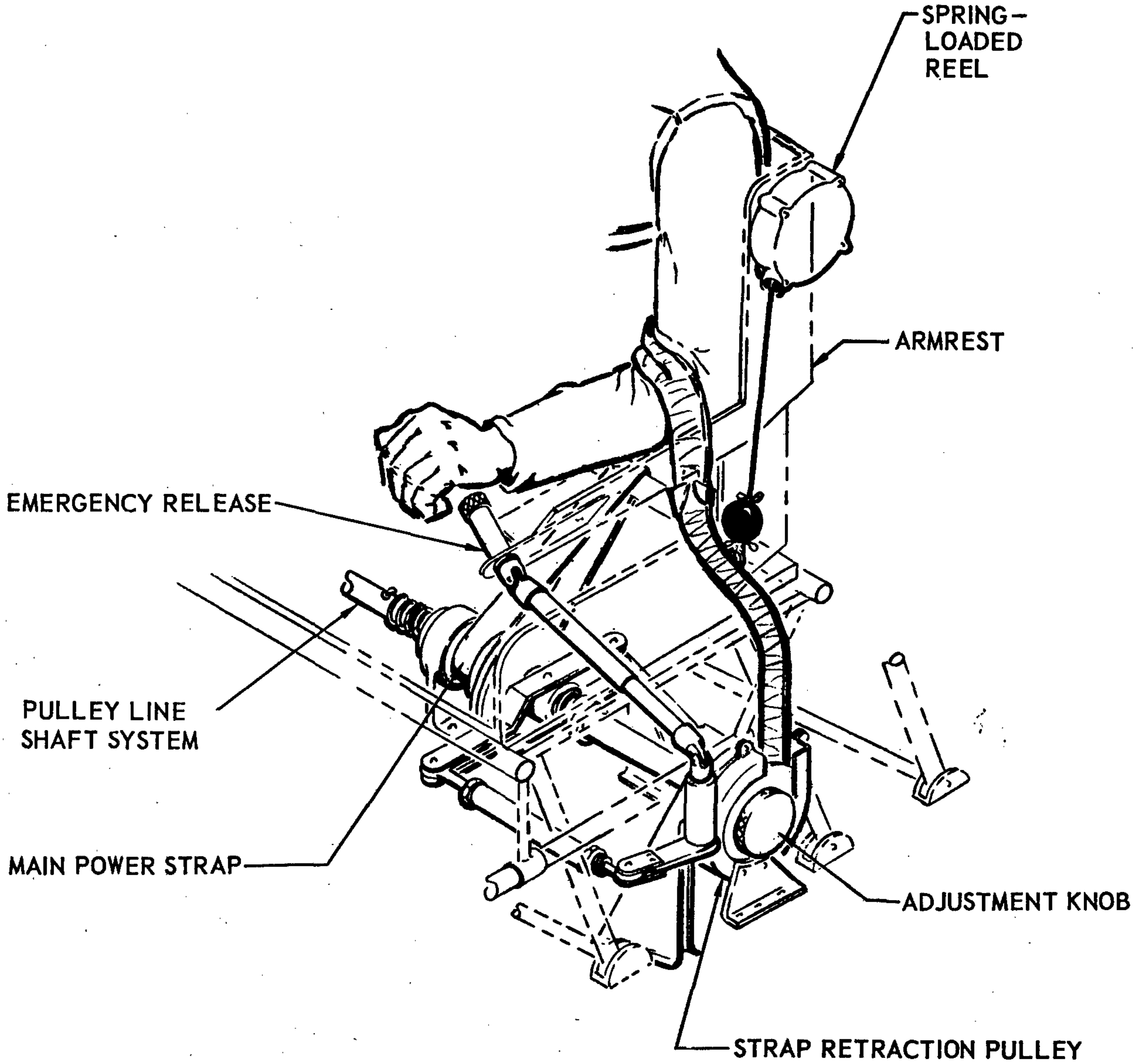


FIGURE 26 ARM RETRACTION SYSTEM

the required 24 inches of retraction. The spring-return device is a modified manual harness reel which is much heavier than required. An emergency egress control is mounted on the left-hand hold and can be used to declutch the pulleys from the line shaft. In the unrestrained condition, full arm mobility is afforded without extending spring-loaded fasteners. If the shoulders are moved forward several inches they will have to start extending the spring reels.

D. Leg Retraction

Leg retraction in the conceptual zipper system would be accomplished by a cable-driven trolley driving the zipper slide. In a conceptual version of the design chosen for testing, a linkage system would bring the leg cover back and down to position the legs. The test system uses the same pivot position as the unmechanized system and mechanically rotates the cover back over the knees and calf to demonstrate the concept. Rotation and adjustment is accomplished through linkage to the test fixture employing seat motion for rotation and a friction-lock variable-length link for adjustment. The distance from the knees (where the antisubmarining loads are reacted) to the pivot point generates a moment imposing high loads on the linkage and adjustment. In addition, the reaction on the grounded link would add to the inertial load imposed by the crewman and his restraint in computing loads on the seat structure. To prevent this loading, the leg cover is supported from the upper seat frame by locked harness reels which are unlocked by the power system to cycle to the unrestrained position. A similar arrangement might be used on an operational system with the cables carried to vehicle structure to permit a lighter seat. The test system is illustrated in Figure 27.

E. Power Systems

Selection of a restraint-support power actuating system for an operational restraint system would depend heavily on the flight vehicle in which it was installed. Aircraft normally have large electrical generating and hydraulic power control systems. Spacecraft may have small capacity, continuous power systems, or large supplies of stored energy which is normally dissipated at a low rate. This study has therefore been primarily concerned with the power actuating requirements and a breadboard test system.

Assuming a crewman with his personal equipment and restraint-support devices weighs 250 pounds and has to be positioned through an average of one foot at a 5 G stress level in a reasonable positioning time of one-half second, a minimum of 4-1/2 horsepower is required. Add friction, acceleration and deceleration, and the energy required for pretensioning, plus actuator efficiency, the result will prove to be on the order of a 10 - 15 horsepower input. From the standpoint of total energy, however, only about 5 HP sec or 0.002-kilowatt hours are required.

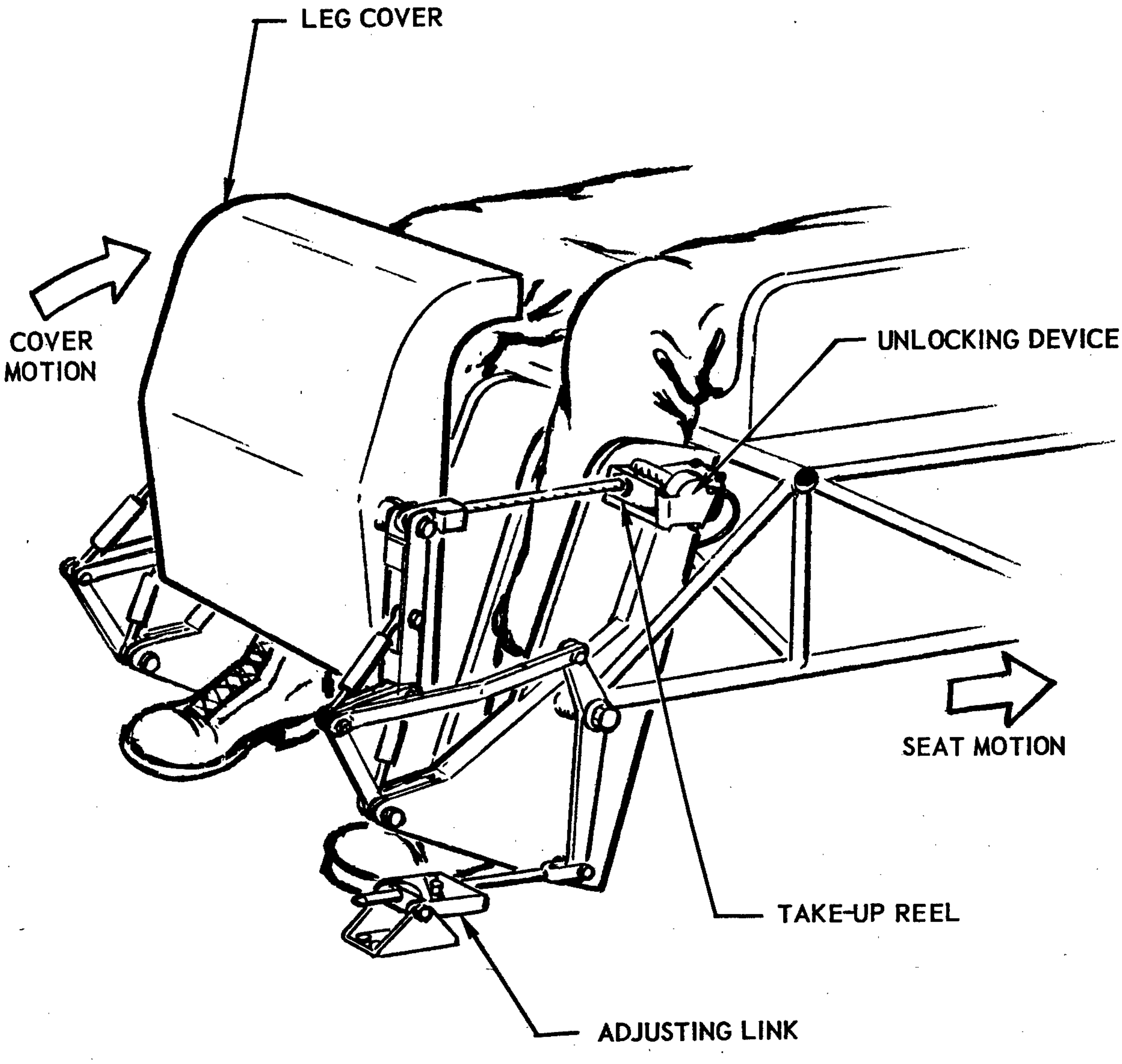


FIGURE 27 LEG RETRACTION SYSTEM

Electrical actuation is virtually eliminated in all systems by the size of the actuators required and in most systems by current flow requirements. Hydraulic or pneumatic actuators would be of reasonable size if operated at 3000 psi or above. However, the routing of 3000 psi air or combustible and toxic hydraulic fluids around a crew station should be avoided. This basic problem is currently being solved in ejection-seat hardware by ballistic actuators operated on a one-cycle basis. Currently available ballistic systems are not rechargeable and a new system would have to be developed. Stored high-pressure gas or cryogenics injected into a small chamber and permitted to build up pressure could be used for a power source to drive an independent hydraulic system. This hydraulic system could be contained entirely in the environmentally controlled cabin and use water or some other non-toxic substance for a working fluid.

The test system utilizes an air-powered, closed-hydraulic system for primary actuation. Low pressure air was chosen for its availability at the test site and the availability of commercial components. The hydraulic portion provides a smooth, controlled speed stroke for the seat cycling cylinders and has the ability to instantly lock the seat by cutting off oil flow. Pilot-operated oil-check valves provide the locking feature. Leg restraint reels are unlocked and torso reel seers are pulled by small air cylinders. This system could not be designed to reposition in the desired 0.5 seconds with reasonable size components at the low pressures utilized. The system will stroke in 1.0 to 2.0 seconds, which should adequately verify its characteristics. A schematic of the system is illustrated in Figure 28.

F. Conceptual System

Figure 29 illustrates the conceptual versions of the previously described restraint-support-prepositioning systems as they might appear in an ultimate, over-all system. Note the improvements in weight, bulk, and detail hardware that might logically be provided by further development and detail design for an operational system. Cables and cable retainers are not required on the breastplate of the integral hard-shell seat back. The crewman can engage or disengage his hard-shell by a control lever that actuates pin locks at the floating hip pivot and behind the shoulders. Breastplate buckles are a low-profile type and smoothly rounded. The ribbed shell, which is integral with a metal frame, is much lighter than the research configuration. Lateral head-support pads are mounted on the vehicle structure and independently driven. Light-duty harness reels retract the head-and arm-restraint straps and light spring-returns hold the arm straps up out of the way. A universal seat is used, permitting rapid crew rotation. The knee and leg cover is articulated to fold back and drop down. This device might profitably be integrated with vehicle structure in a specific design.

It is difficult to describe or even to forecast the full potential of a research system because of the unknown possibilities for satisfying other mission requirements with the hardware of a particular system. Possible applications of portions of this system's hardware include: use of the hard-shells and water-filled liner for radiation protection; using the torso shell as part of an extravehicular suit for protection from micrometeorites, and as a load path and mounting device for a space

NOTE: SYSTEM SHOWN STROKING TO UNRESTRAINED CONDITION

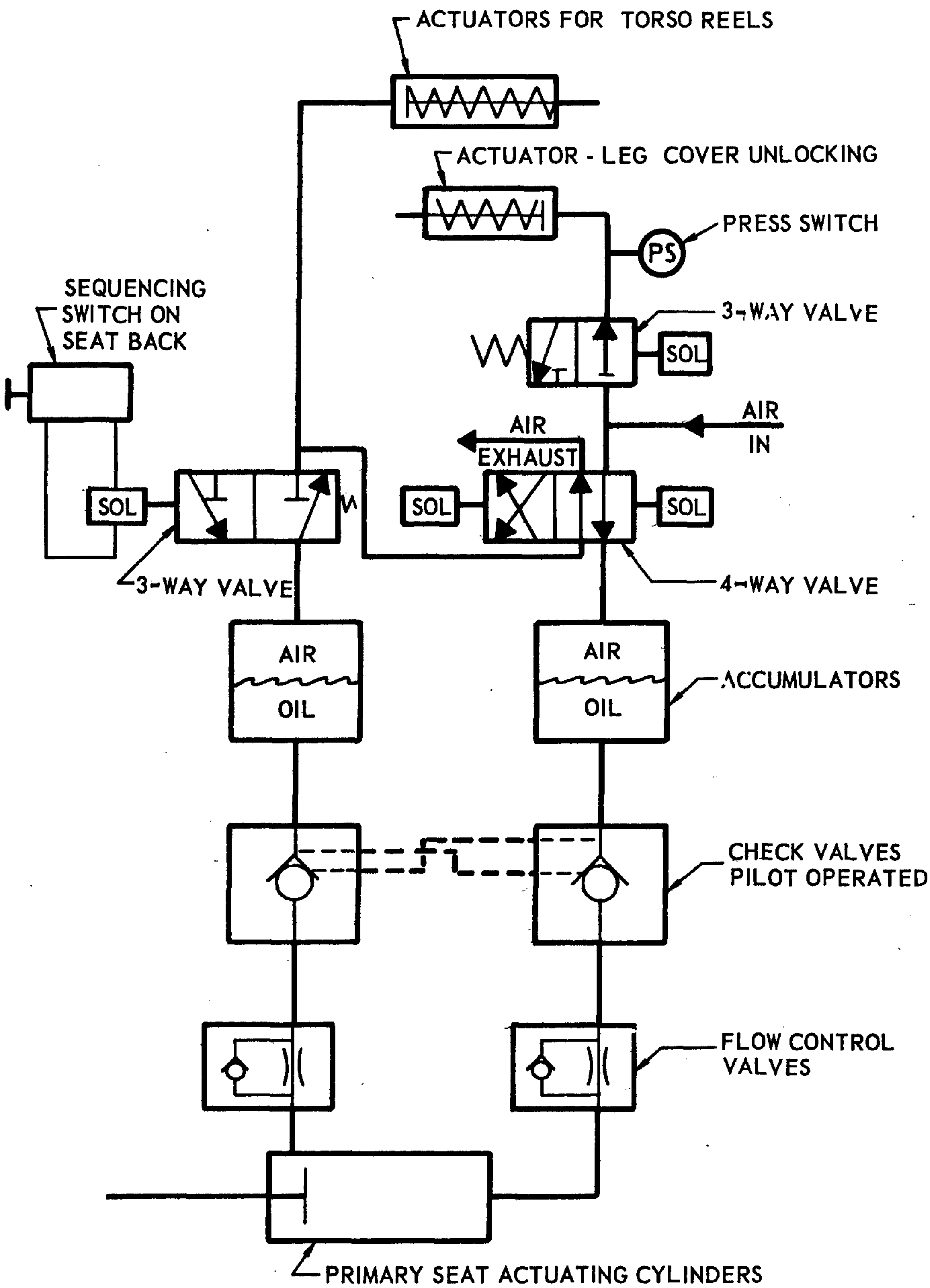


FIGURE 28 POWER SYSTEM SCHEMATIC

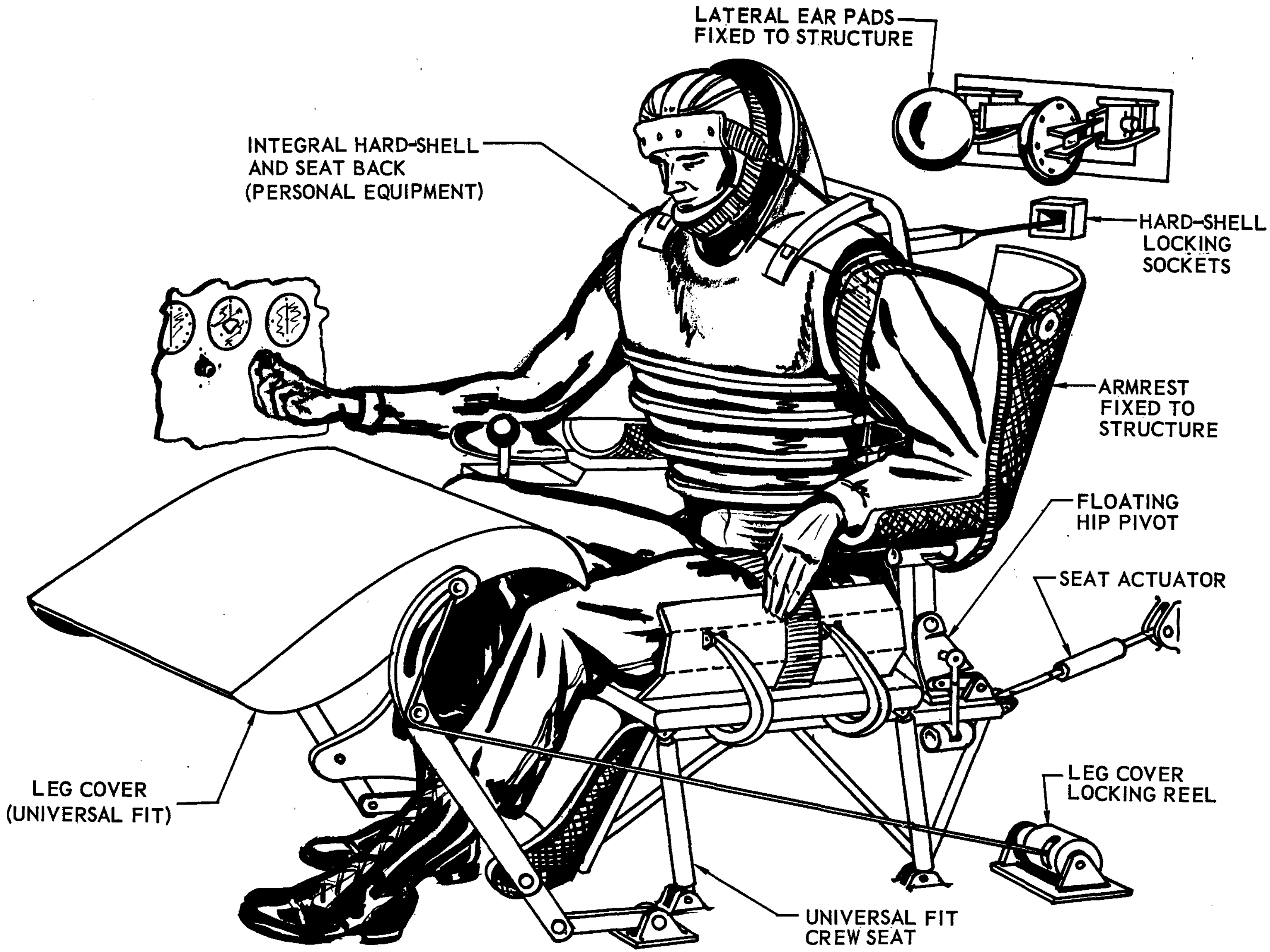


FIGURE 29 OPERATIONAL CONCEPT

maneuvering unit; socketing the torso shell attachments into fittings at standing work stations for protection and leverage; using the liquid in the liner as an emergency water supply; and using oxygen as a power source and, at the same time, as a supplement to the breathing atmosphere.

SECTION X

CONCLUSIONS

Several conclusions can be drawn from the study and fabrication accomplished in this program. These conclusions are outlined in the following paragraphs.

A. Acceleration Environment

Future manned flight systems, particularly space systems, will generate an acceleration environment different from the environment for which the current restraint concepts were developed. Significant new accelerations include long-duration accelerations, multidirectional accelerations and accelerations with a low total energy and a high peak magnitude.

B. Human Engineering

In the performance of this program, it was necessary to have a working knowledge of anthropometry and the dynamics of the human body and a background of human tolerance test data. In addition, a thorough study of the structure, arrangement, and physiology of man was conducted early in the program. These background data were utilized throughout the concept development and detail design phases of the program. Consideration of man's internal configuration in developing restraint and support concepts was found to be particularly helpful in designing for previously untested stress levels. It was sometimes found that current restraint concepts that performed satisfactorily were not utilizing optimum load paths in the body. From this study, it was concluded that the details of human structure and arrangement should receive the same attention from the designer as the mechanical details of restraint and support mechanisms.

C. Loading Analysis

Inertial loads were calculated for each human body element at the peak G specified and converted to the minimum unit bearing pressures that would produce equilibrium. This procedure established structural design criteria for each element of the restraint and support system. It also provided perspective in establishing bearing areas and surfaces for each body element. A similar loading analysis would be helpful in any future restraint system design, particularly if the technique was refined with additional data on body element weights, areas, and weight distributions within major body segments.

D. Rigid Contoured Restraint

From the analysis conducted in this program, supporting the human body with rigid contoured restraint elements appears to provide a high level of body protection. These rigid restraint devices may be required to move relative to structure to attenuate peak impact levels; however, maintenance of natural body shape requires rigid contoured support elements. This method of protection should be studied in detail with particular attention to the design problems of fit, comfort, and mobility that inherently detract from the concept.

E. Prepositioning and Pretensioning

It has been recognized for some time that mechanized devices to position a crewman and pretension his restraint would be an asset. As restraint and support systems became more complex these mechanized systems became more desirable. Some mechanized devices have been incorporated in ejection seats for a one-time operation and have proven satisfactory.

In this program an attempt was made to mechanize an entire restraint system for repeated applications. Although the system developed is a test configuration, it is compatible with space-type hardware development. From this design study, it was concluded that it was feasible to develop a prepositioning and pretensioning system for advanced flight systems.

SECTION XI

RECOMMENDED FUTURE RESEARCH AND OPERATIONAL DEVELOPMENT

The next logical step in the program is a thorough manned test evaluation of the research hardware developed in this program. This testing is currently in progress. When test results demonstrate the protection potential of the various concepts, much research and development must then be accomplished to produce operationally acceptable configurations. In addition to any basic deficiencies discovered in the concepts or designs--and in any other avenues of further protection research which may appear--as a result of the tests, the following development items are recommended to be programmed.

A. Hard-Shell Operational Configuration

Torso hard-shells developed for this program were designed to demonstrate the protection potential. Much of their weight and bulk can be removed by designing a ribbed structure which is integral with steel frame seat back, and by a more exact and less conservative stress analysis backed up by structural testing. The operational feasibility of the hard-shell can also be improved by an integral back design and a floating hip pivot. A design optimization study with fabrication and structural proof tests is recommended.

B. Lining Materials

The LIQUIFOAM lining material developed for this program is based on sound dynamic response and comfort reasoning. It has not yet been adequately tested because the manufacturing quality control of the process was still inadequate and could not be perfected within the scope of the program. Similar process problems have been resolved in many current products, and other manufacturing techniques could be advantageously employed. It is recommended that LIQUIFOAM development be continued as a separate development item until it is satisfactory for manned testing.

Microballoons also demonstrated a potential of considerable promise for lining materials at a very attractive weight. Their primary known disadvantage is the difficulty in pumping them to provide a compact impact liner. Microballoon response characteristics should be investigated and, if proven satisfactory, methods should be studied for injecting, relaxing, retaining and compartmenting, followed by a fabrication and test program.

C. Operationally Acceptable Power System

Both independent power systems and systems integrated with the vehicle power supplies might be acceptable. Several systems might therefore be profitably researched. It would be extremely expensive to accomplish this research by building a series of test systems representative of operational hardware. A study program is recommended in which specific requirements are established, power system concepts are evolved, promising concepts are designed and one or more systems is breadboarded for tests.

D. Prepositioning and Pretensioning Concepts

Positioning and tensioning systems can assume an infinite variety of forms. Several of these forms were investigated during this program and one over-all test system was developed. With increasing requirements being established for powered articulation of crew restraint-support systems, more conceptual development and test effort should be directed toward this area. This effort should be concentrated on techniques for positioning, manipulating, restraining, and tensioning the man within his structural limitations and with a minimum of encumbrance. For this recommended program, power actuation can be assumed to provide any pull, push, or rotation required. When optimum restraint concepts have been evolved, the resulting actuator requirements for operational hardware can be met with sufficient straightforward design and development.

E. Restraint System Test Data

Current restraint configurations were evolved by gradually increasing the protection of the time-proven strap system. Logical improvements were developed by correcting deficiencies demonstrated in service and by tests. These improvements were verified by further testing. The development process has been highly refined (Ref. 77) and has utilized the full potential of the strap concept.

In the program described in this report, new basic concepts were to be developed. Manned test data were needed to establish requirements. Most of the available data had been collected using strap restraint and correlated on the premise that it would be used to evaluate and refine strap systems. A requirement for more basic data, independent of the restraint configuration, was apparent. Design information which was sought and generally not found in the test literature includes: unit pressures endured under the restraining device, shear and tension loads generated within the body and its appendages, total excursions of one body element relative to the adjacent element, actual accelerations applied to the extremities such as the head, etc.

A study program is recommended to establish and correlate the test data which engineers require to design a new type of restraint system. The recommended study would produce a well-defined problem statement or test goal for the guidance of manned test experimenters and should reduce the total number of human exposures required.

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APPENDIX I

AREAS OF VULNERABILITY TO IMPACT STRESS IN THE HUMAN BODY

INTRODUCTION

Human tolerance limits to impact and long-term acceleration forces have been inadequately delineated in spite of the tremendous amount of work done. Reported data, in many cases, are vague; and, overall, the available information has a low percentage of reliability. To a major degree, the fault lies in the method of measuring G forces. G meters attached to various points on seats, restraint harnesses, and the occupant have widely differing readings during the same test. The dynamic response to acceleration forces of the seat-restraint harness occupant unit must be considered in measuring G loads imposed on various parts of the occupant.

While quantitative data from numerous tests of questionable validity are available for whole body acceleration, little attempt has been made to define rigidly the tolerance limits to structural loads of the component organs and tissues of the human body (e.g., muscle, mesentery, blood vessels, liver, heart, bones, intact arm, etc.). A plethora of papers on airplane and automobile accidents, football, boxing and skiing injuries, etc., are, at best, semi-qualitative. No compendium of information on the resistance of organs and tissues to mechanical forces exist. Yet the total strain (the change in linear dimensions of an object as a result of the application of a force-- for example, the liver or the aorta, particularly in the region of the ductus arteriosus) may well be the most important factor in determining how to protect against incapacitating or fatal injuries.

Considerable study of bone structure and fractures has been done on either dried specimens, or bones in and from embalmed cadavers. Much of this information may be misleading in that many authors have not seen fit to specify the source and "freshness" of their experimental material, thus making their data meaningless. For example, 25 in. lb. is sufficient energy to fracture a dry skull, but an intact head must be struck with a force of 400 - 900 in. lb. in order to produce a fracture.

Because of the apparent inadequacy of the literature on the subject at hand, it is impossible to do more than point out the relative susceptibility to injury of organs, tissues, and structural units.

A breakdown of the human body into specific areas of vulnerability may serve to point out the relative resistance to injury by G forces of these body components. One class of injuries which a properly designed restraint system virtually eliminates from consideration are the fractures. (While fractures are listed as possible injuries, the probability of occurrence is low under the conditions circumscribed by this report.) The use of high-impact low-rebound foam padding as an absorber for impact G-forces is the major deterrent to bone breakage; the restraint system, restricting mobility by maintaining normal skeletal alignment and by directing the occupant into the foam padding, regardless of direction of G force, serves to utilize the energy absorbing characteristics of the padding.

Even though fractures are ruled out because of the high inertial loadings of body parts, small movements will place large stresses on supporting structures (such as the meninges of the brain); and the resultant injury possible under these circumstances will resemble those found secondarily in cases of fracture from blows.

The organ weights used for the determination of inertial loads of the internal organs were not from a 95th percentile man, as defined by WADD-TR56-30. Data on organ weights from the WADD Handbook of Biological Data and several standard anatomy texts all tend toward organ weights for the average man of the general population, namely, a 65 - 70 kg man, whereas the 95th percentile man weighs over 90 kg (200.8 lbs). Extrapolation of organ weights on the basis of a simple arithmetic ratio was not attempted due to the inherent fallaciousness of data thus derived; the weight of a specific organ is not a linear function of body weight.

However, the inertial loads determined for 60 G transverse, 30 G positive, and 20 G negative are of interest in illustrating the tremendous forces to which internal organs are subjected and the forces which they themselves generate; the latter forces act on supporting mesenteries, connecting ducts and vessels, the diaphragm and body walls. The malleability, flexibility, plasticity and flaccidity of the viscera permits movement. While torso movement may be arrested, visceral movement is restricted only by other internal structures which are also subject to injury. This type of trauma can be incapacitating or fatal.

Following is a list of vulnerable areas, in a table of approximate inertial loads for the positive, negative, and transverse G limits of this restraint system.

TABLE I

NORMAL WEIGHTS AND INERTIAL LOADING OF ORGANS VULNERABLE TO IMPACT STRESS

Organ	Wt. at 1G in pounds	Inertial Load at 60G Transverse	Inertial Load at 30G Positive	Inertial Load at 20G Negative
Brain	3.3	198.0	99.0	66.0
Spinal Cord	0.066	3.96	1.98	1.32
Eyes (2)	0.066	3.96	1.98	1.32
Teeth (no fillings)	0.044	2.64	1.32	0.88
Salivary Glands (6)	0.11	6.6	3.3	2.2
Thyroid Gland	0.044	2.64	1.32	0.88
Lungs (2)	2.2	132.0	66.0	44.0
Heart	0.66	39.6	19.8	13.2
Blood	13.53	811.8	405.9	270.6
Liver	3.74	224.4	112.2	74.8
Spleen	0.33	19.8	9.9	6.6
Kidneys (2)	0.66	39.6	19.8	13.2
Pancreas	0.154	9.24	4.62	3.08
Adrenal Glands (2)	0.044	2.64	1.32	0.88
Total Gastrointestinal Tract	4.4	264.0	132.0	88.0
Stomach	.55	32.0	16.5	11.0
Small Intestine	2.42	145.2	72.6	48.4
Upper Large Intestine	0.297	17.82	8.91	5.94
Lower Large Intestine	0.33	19.8	9.9	6.8
Urinary Bladder	0.33	19.8	9.9	6.6
Prostate Gland	0.044	2.64	1.32	0.88
Testes (2)	0.088	5.28	2.64	1.76

A. Head

1. Brain (Figure 31)

Movement of the skull on impact sets the brain into motion. Deformation of the soft brain tissue occurs rapidly. The high inertial load, or effective weight increases the possibility of injury. Shearing forces acting on the meninges can cause extensive damage, particularly in the case of disruption of the highly vascularized cranial pia mater where any tearing would rupture blood vessels. Compression of vital centers by edema resulting from hard contact with the skull or squeezing by the processes of the inelastic fibrous dura mater may cause damage.

2. Face (Figure 30)

a. Bone - Complete or depressed fracture of facial bones is possible.

(1) Nasal (2) Zygomatic	The bones are of light structure and are easily fractured and/or disarticulated although the possibility of either occurrence is small.

(3) Maxilla - thin, weak, will fracture, easily perforated.

(4) Mandible - green-stick fracture and/or dislocation of the jaw is possible; the latter is more probable. In order to take full advantage of the increased structural strength of the clenched jaw, the use of an individually fitted mouthpiece of the type designed by dental and medical authorities for participants in contact sports, as recommended in this report, will minimize injury to the jaw.

b. Eye - Well protected by bony socket except anteriorly (Figure 32)

(1) Bulb of eye and associated muscles - Forty cps vibrational frequency may damage it by cavitation of the fluid media. Conjunctival petechiae and/or opthalmalgia often occur following impact. At the inertial loads indicated the extrinsic musculature may be stretched or possibly ruptured (the muscles plus eyeball may be visualized as a slingshot with the eyeball as the shot, the muscles as the sling; sudden removal of G forces decreases the inertial load allowing the muscles to snap back thus imposing secondary forces on the bulb of the eye). In this particular instance, a decrease in elasticity of the musculature might be considered desirable.

(2) Retina - Retinal detachment may result from increased intraocular pressure and/or cohesive forces of the vitreous humor. Venous spasm and hemorrhage have been observed in the retina as delayed effects.

(3) Optic Nerve - Non-fracture injuries cause little or no damage. Stretching and involvement in retinal detachment under high G is a possibility.

(4) Blood Vessels - Engorgement, rupture, and hematoma have occurred.

(5) Intra-ocular Pressure - Variations interfere with vision. Excess pressure on the eyeball may initiate the ocular-cardiac reflex arc which may inhibit heart action, the degree of inhibition being subject to wide variation.

B. Vertebral column. With the head restrained, whiplash injury (hyperextension and/or hyperflexion) is held to a minimum. However, vertical compression, which may cause injury because of the very small load area, is more difficult to avoid; proper arm support aids in combating compression effects. Muscle and tendon tearing and intervertebral disk damage can result from hyperextension or compression (Figure 34).

Dynamic tolerance of the body is directly related to the tolerance of the spinal column. Experiments on live human subjects place this tolerance at 26 G if the force acts for 0.0005 seconds. Resistance to breaking loads has been reported for individual vertebrae because of the variation in load-bearing area, size, and shape among the vertebrae and intervertebral disks; the over-all resistance or tolerance to compressive forces of the spinal column is governed by the strength of the weakest link in the chain. Although L-1 has a breaking load of 2200 lbs (in a person weighing 70-90 kg, a 40-kg load is the approximate weight borne by the vertebral column in the erect posture) calculations based on the strength and the percentage of the load carried by the individual vertebrae indicate the L-1 would collapse after the absorption of approximately 72.3 ft. lbs. of energy. If a force is rapidly acting, great stress in the lumbar region is produced by the smallest trauma. Protection of the back from the intensity and frequency of changes occurring in the shape of the disc probably cannot be derived from muscular reaction.

Intervertebral discs are well adapted for withstanding normal compressive forces. Since the structure of the discs is such that they are almost completely compression resisting structures, the compression attenuation by the armrest and over-all energy absorption by the restraint system padding insures a high degree of safety for the occupant.

1. Neck (Figure 31)

a. Carotid Sinus Reflex Arc - Properly fitted equipment obviates any possibility of stimulating this reflex arc.

b. Carotid Artery and Jugular Vein - According to some investigators the brain seems curiously immune to damage in traumatic cyanosis produced by relatively slow compression of the chest, although the face, scalp, and neck show severe petechial hemorrhage. Engorgement of the blood vessels of the neck may also occur.

c. Larynx - A blow over the larynx can cause interruption of the free flow of air to the lungs due to edema and swelling of the associated mucous membranes and soft tissues.

C. <u>Trunk</u> (Figures 33 and 34)

1. Thorax

It has been suggested that a wave of high venous pressure transmitted from the compressed thoracic cavity can cause injury to structures of the head and neck.

a. Ribs - Compression of the rib cage and the subsequent rebound can both cause injury. Prolonged compression restricts breathing. Sudden compression of short duration may fracture the ribs. The point of greatest weakness is located at the arc of the mid axillary line or at the posterior angle of the rib. Upon fracture, the broken ends tend to be driven inward, lacerating the pleura and even the lung itself. The possibility of rib fracture in a properly designed restraint system is remote.

b. Pleural Cavities (Figure 36)

(1) The chest and abdominal muscles are involved in breathing. Any restriction by the restraint of abdominal distention and chest expansion for extended periods will impair breathing to the point of suffocation. This restraint system does not interfere with respiratory movements. The inertial loads noted for the lungs show the need for absorption of G-force energy by the restraint system padding in order to minimize movement of the lung and any resultant stress on the root and pleura. The highly elastic nature of the lungs offers a measure of protection.

(2) Bronchi - Constriction as the result of mechanical obstruction and/or reflex action caused by regurgitated stomach contents entering the trachea is a definite possibility. Motion sickness cannot be prevented by a restraint system. There is a distinct likelihood of tumbling, pitch, yaw, and roll beyond calculated limits in experimental vehicles; pharmacological means of prevention of regurgitation may be indicated (Figure 39).

c. Mediastinal Cavity

(1) Heart (Figure 39) - Compression anterio-posteriorly can squeeze the heart between the sternum and thoracic vertebrae, extruding it to one side of the chest cavity, and thus producing pain symptomatic of a heart attack. Cardiac output may be reduced by diaphragmatic herniation. The inertial loads shown for the heart are indicative of the stress to which the attached vessels and supporting structures of the heart will be subject.

(2) Thoracic Descending Aorta - Laceration inferior to the ductus arteriosis can occur, the probability increasing if there is an occlusion of the large blood vessels of the lower part of the body when impact forces are applied.

(3) Gas pressure or other factors in the GI tract may cause regurgitation of stomach contents resulting in blockage of the trachea and bronchi.

(4) Constriction of the trachea by reflex action or mechanical interference may limit air flow to the lungs.

2. Abdomen (Figures 36, 37, 38, 39, and 40)

The solid viscera in the abdomen are relatively well protected; however they incur contusion, laceration, and rupture more frequently than hollow viscera. The explanation advanced is that the solid viscera have more fixed attachments, thus permitting less movement of the organ.

The high mobility of hollow organs and the fact that their walls are collapsible thus providing attenuation to a blow, have lessened the frequency of contusions, lacerations, and ruptures even though these organs occupy the major portion of the peritoneal cavity.

Injuries to the diaphragm are infrequent; but trauma to the abdominal wall alone, without internal injury, occurs quite often. The right rectus muscle is quite susceptible to injury, but is hard to diagnose due to the rectus rigidity resembling a symptom of appendicitis.

Blunt abdominal trauma carries a higher mortality rate than penetrating injuries, i.e., 20% - 30%. Compilation from hospital records indicate that the frequency order of injury is as follows: Spleen 26.2%, Kidneys 24.2%, Intestines 16.2%, Liver 15.6%, Abdominal wall 3.6%, and 7.7% comprised of retroperitoneal hematoma, mesentery, pancreas, and diaphragm. The present theory on injury mechanisms is based on the conclusion that the extent and type of injury are determined by whether the force is applied slowly or suddenly. Because the viscera have some degree of mobility, a slowly applied force is less apt to cause injury than a sudden, sharp, localized blow. Furthermore, a sudden application of pressure is more likely to rupture solid than hollow viscera. The elasticity of the viscera decrease with age; thus, younger individuals are better able to tolerate trauma. Internal injury may be lessened or obviated by a well-muscled abdominal wall; a relaxed abdominal wall can permit splenic or liver rupture by a comparatively light blow.

a. Gastrointestinal Tract (Figures 36 and 37)

(1) Stomach - Can shift, may be ruptured or forced up through the diaphragm at several points.

(2) Small Intestine	Adhesions may occur as the result of impact forces.
(3) Large Intestine	

The possibliity also exists of tearing the mesenteries of the abdominal cavity.

b. Solar Plexus - Located behind the stomach, it can receive enough impact force to inhibit breathing, particularly in view of the high inertial loads as listed above.

c. Spleen - Very friable, highly vascularized, extremely susceptible to injury, it is easily ruptured on abdominal impact. Restricted movement of the organ, coupled with low structural strength makes torso restraint of prime importance. Maximum absorption of acceleration energy by restraint system padding decreases the probability of splenic movement and ensuing trauma.

d. Pancreas - Compound, racemose gland; similar in appearance to, but less compactly arranged than, the salivary glands. Displacement, with subsequent tearing possible. Intimate apposition to abdominal blood vessels, common bile duct, intestines and peritoneum makes injury to these structures possible.

e. Liver - Friable, easily lacerated, highly vascular, held in place by the inferior vena cava, hepatic veins and the coronary and triangular ligaments, which attach to the diaphragm. Lateral movement is limited by the falciform ligament. The liver has the highest density of the abdominal organs and the highest inertial load of any organ. Low structural strength and restricted movement make the liver quite susceptible to injury.

f. Fall Bladder - A muscular membraneous sac, thin walled but strong, with small chance of trauma.

g. Kidneys - The position in the body and a degree of mobility, in addition to the protection afforded by the ribs, serve to minimize the possibility of injury. Contusion and rupture may result from impact forces of sufficient magnitude, but the fibrous renal fascia enable the kidney to withstand most forces.

h. Descending Aorta - Aneurysm may develop in the aorta if major blood vessels are occluded. (The only observations of violent movement impinging on the inner surface of the abdomen have been in cases of fetal motion in utero. Not uncommon are kicks hard enough to cause the mother to double up as if from a hard body blow. G forces developed are probably of the order of 5 - 10 G. With inertial loads noted, organs have a large effective weight. Contact with the abdominal wall can be painful and temporarily disabling.)

3. Pelvic Cavity (Figure 40)

a. Urinary Bladder - When distended, the bladder, a musculo-membranous sac, is easily ruptured, but empty is well protected by the surrounding bone and muscle.

b. Rectum - The buttocks must be held together by the contoured seat to prevent prolapse of the rectum or the development of hemorrhoids.

c. Prostate - Has a fibrous capsule, highly muscularized stroma, of great density and is not easily torn.

d. Ureters - They may collapse on impact or muscle spasm may cause constriction. Tearing or rupture of the tube is highly unlikely.

e. Inguinal Canal - Those with congenital disposition to inguinal hernia should be eliminated from consideration for space flight. Herniation may cause compression damage to the vas deferens. A corset of the type included in the restraint system design will prevent such injury.

f. Testes — The corset mentioned above or a jock strap with cup offers good protection.

g. Scrotum

D. Upper Extremities (Figures 33, 34, and 35)

1. Shoulder Girdle

There is a great flexibility and tendency toward displacement injury of the shoulder girdle. The main attachment point at the manubrium is easily disarticulated.

a. Clavicle - The clavicle is comparatively weak and easily fractured.

b. Scapula - The scapula is easily dislocated.

2. Humerus

May be dislocated and/or fractured as the result of direct trauma to the bone. Pinching may cause injuries to the overlying nerves, muscles and blood vessels.

3. Ulna

Fracture may occur as the result of overloading the area. The exposed nerve by the olecranon process (elbow) may be injured and incapacitate the lower part of the arm. Injuries to nerves, blood vessels and muscles occur due to displacement of bone fragments.

4. Radius

Fractures and dislocations are common.

5. Hand

The hand is incapacitated if the ulnar nerve is pinched or blood vessels of the arm are disrupted. Direct force may lead to fractures, etc., as in other areas.

E. Lower Extremities (Figures 33,34, and 35)

1. Pelvis

The weakest point of the pelvis is the sacroiliac joint joining the pelvis to the vertebrae column. The pelvis may be fractured under impact and separation of the two halves in front of the symphysis pubis occur.

2. Femur

If the femur is not supported during impact, a dislocation or fracture or both may occur. Fractures of the femoral neck occur and lateral impact may drive the head of the femur through its pelvic socket into the pelvis. Support of the greater trochanter will help bear the weight of the upper part of the trunk and stabilize the body in lateral accelerations up to the limits noted above.

3. Patella

The patella protects the knee joint but it can lock the joint if it is fractured or dislocated. Damage to knee joint ligaments can occur if the relationship of leg and knee is not kept within inherent elastic limits. Fragments from fracture of these may also lock the knee joint.

4. Tibia

The tibia may be fractured if it is not supported relative to the thigh.

5. Fibula

The fibula can be fractured and/or dislocated.

6. Foot

The foot should be restrained and may be incapacitated during high G stress. Also dislocation of ankle joint occurs if feet are not supported relative to leg.

F. <u>Joints</u>

A blow in the region of a joint may result in injury to the synovial membrane and communicating bursa or more damaging injuries such as stretching and tearing of joint ligaments and capsule may occur. Even more serious is injury to the joint cartilage or fracture of the bones forming the joint surface. This leads to the collection of fluid and hemorrhage within the joint. Disability from ligamentous and joint injuries is prolonged.

1. Synarthrodial Joint (immovable joints)

There is a remote possibility of fracture and dislocation or disarticulation in these joints.

a. Skull Sutures - The articulations of the sutures in the skull are strong and are not easily injured. Separation is apt to occur only in the very young.

b. False Sutures (e.g., maxillae) - A fracture to the false sutures could cause injury to eyes and sinuses.

2. Amphiarthrodial Joints (slightly movable joints)

There may be separation of the slightly movable joints.

a. Symphysis (e.g., symphysis pubis, sacroiliac, intervertebral cartilaginous disc) - These joints may be separated, sprained or dislocated, but extreme forces are required.

b. Syndesmosis (e.g., tibia-fibular articulation) - This joint is weak and may be dislocated by poor support of the foot and calf.

3. Diarthrodial Joint (movable joint)

a. Gliding Joints (e.g., between carpal bones of the wrist and between tarsal bones of the ankle, articular processes of the vertebrae)- These joints are easily sprained and/or dislocated by shearing forces.

b. Hinge Joints (e.g., between humerus and ulna, in the ankle joint, articulations of the phalanges) - These joints are easily disarticulated or sprained by shear loading. The knee joint has no basic stability in its bony structure. Resistance to lateral motions derived from the fact that the lower end of the femur is a bipod and tends to have one condyle in close apposition to the corresponding articular surface of the tibia.

c. Condyloid Joints (e.g., the wrist, or radiocarpal, joint) - These joints are of the type that admit an angular movement in two directions. When an oval-shaped head, or condyle, of bone is received into an elliptical cavity, it is said to form a condyloid joint. This type of joint may be relatively easily dislocated or sprained by shearing or torsion loading.

d. Saddle Joints (e.g., metarcarpal bone of the thumb is articulated with the greater multangular bone of the carpus) - These joints are like the condyloid joints in providing for angular movement in two planes, but the structure is different. The articular surface of each of the articular bones is concave in one direction and convex in another, at right angles to the former. Dislocations and sprains frequently occur in these areas.

e. Pivot Joints (e.g., odontoid process of the axis, proximal articulation of the radius and ulna) - These joints have a rotary movement in one axis and may be sprained or dislocated by shearing or bending.

f. Ball and Socket Joints (e.g., head of the femur in the acetabulum and the head of the humerus in the glenoid cavity of the scapula)- The shoulder joint is the most freely movable joint in the body and most easily sprained and dislocated.

G. Embolism

1. Blood

In practically all injuries to the blood vessels, there is thrombus formation. Emboli tend to become detached thus leading to devitalized areas of vital organs by blood vessel occlusion.

2. Fat Embolism

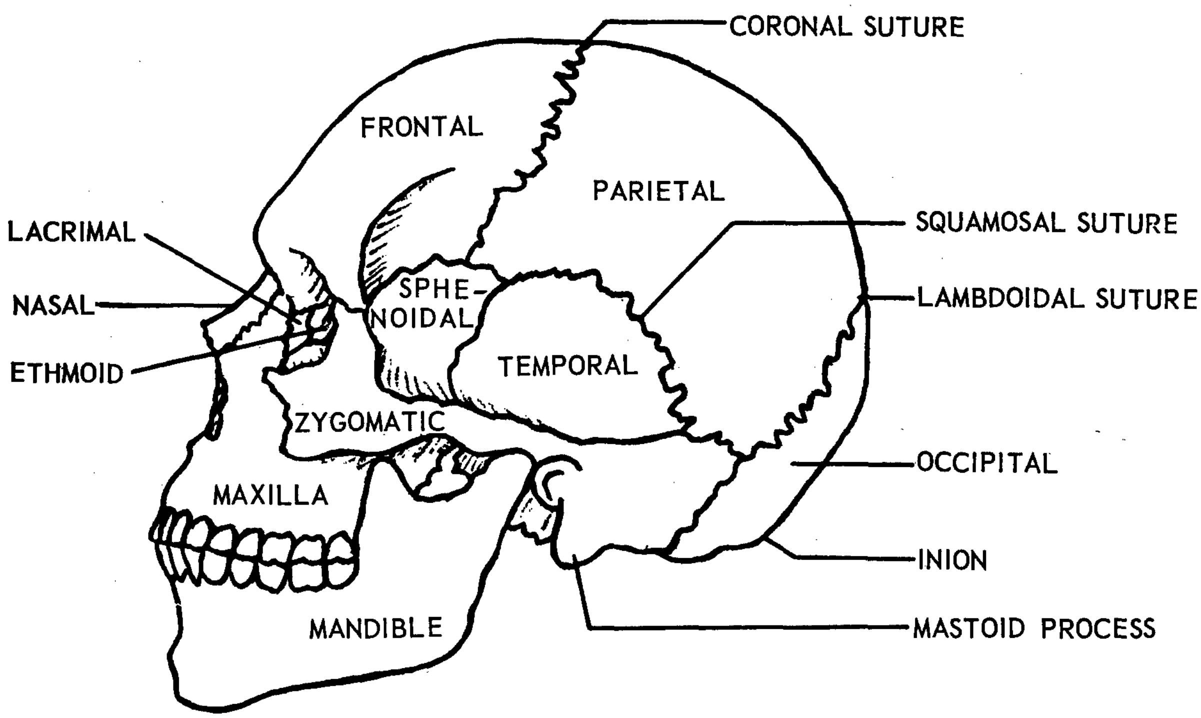
Appears classically after fractures of the tibia and femur, with massive soft tissue injury. Also occurs with non-fat containing bones, concussion, or jarring of the skeleton.

Furthermore, a case for extreme caution is made by the fact that even trivial injuries result in fat embolism. One of the difficulties in associating fat embolism with specific types of damage is the time internal between the traumatic occurrence and the appearance of the fat emboli, the occurrence in other than traumatic cases, and the appearance of the emboli in the greater circulation.

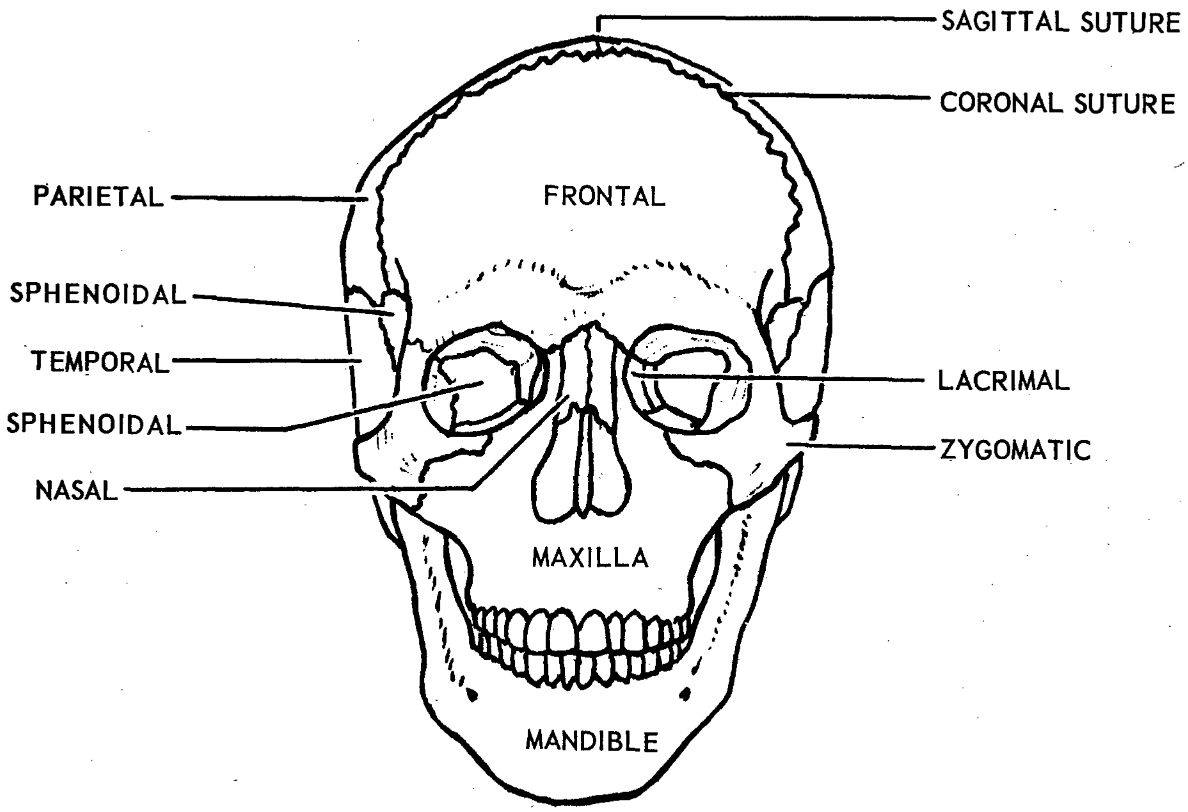
H. Survey of Injuries

A list of injuries resulting from impact is given in Table II. This list is compiled primarily from case histories of accidental falls and suicides, as very few injuries have been experienced in controlled tolerance testing. Rates of onset, peak G, and times at peak G estimated for these exposures must be treated as approximate. Total energy was calculated quite accurately. These case histories serve primarily to indicate the high forces to which human organs have been exposed without serious injury. Case histories wherein the subjects impacted on surfaces that provided broad body-support are particularly significant. A high tolerance is indicated by the data. The restraint designer, having complete control of the body-support devices, should be able to utilize this inherent tolerance.

In the analysis of impact case histories and the determination of restraint system unit loading it is necessary to determine the surface area of the human body. A nomograph for determining whole body surface area is shown in Figure 41. This graph provides a first-order approximation only, as the projected area of specific body elements in a specific direction is usually required.

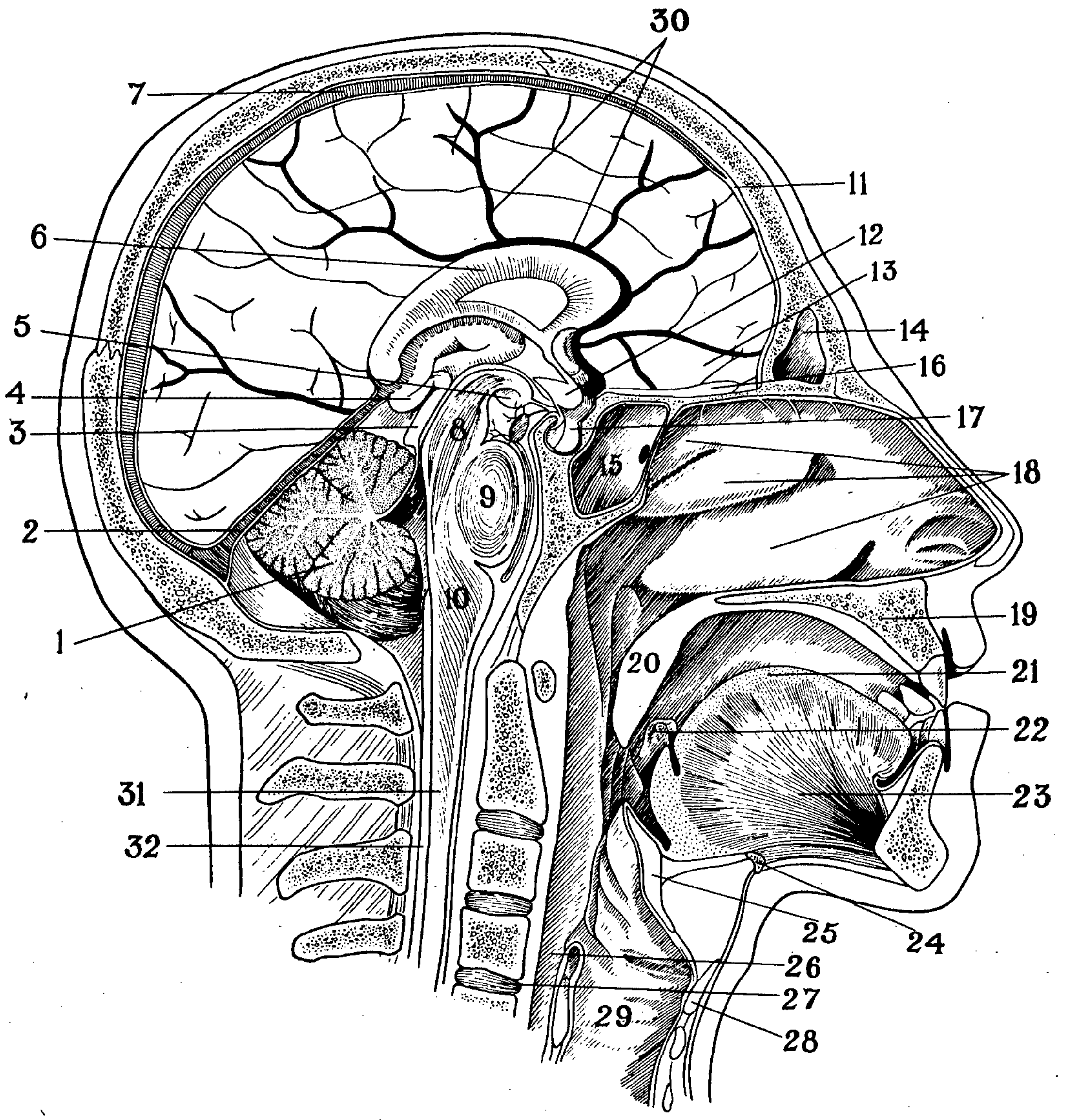


SIDE VIEW OF SKULL



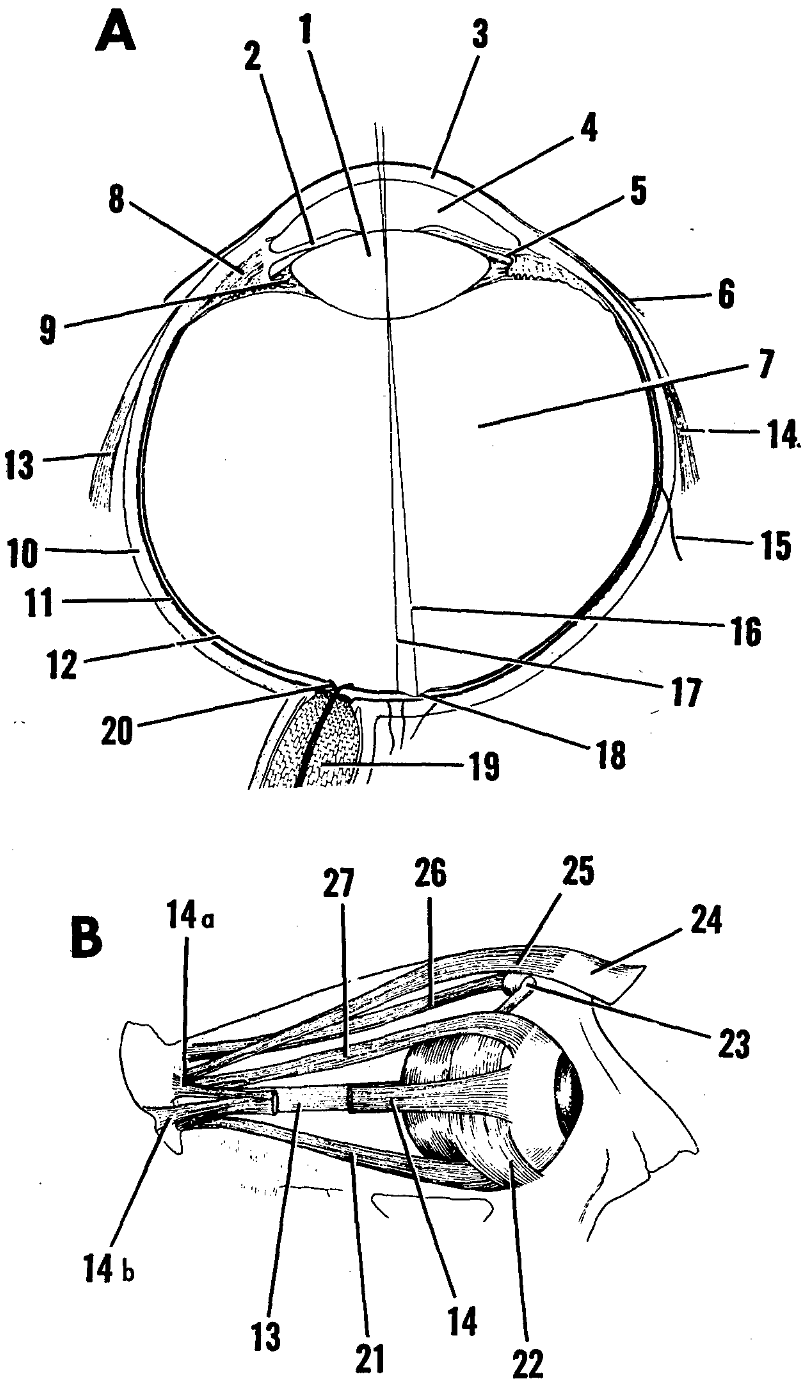
FRONT VIEW OF SKULL

FIGURE 30 SKULL



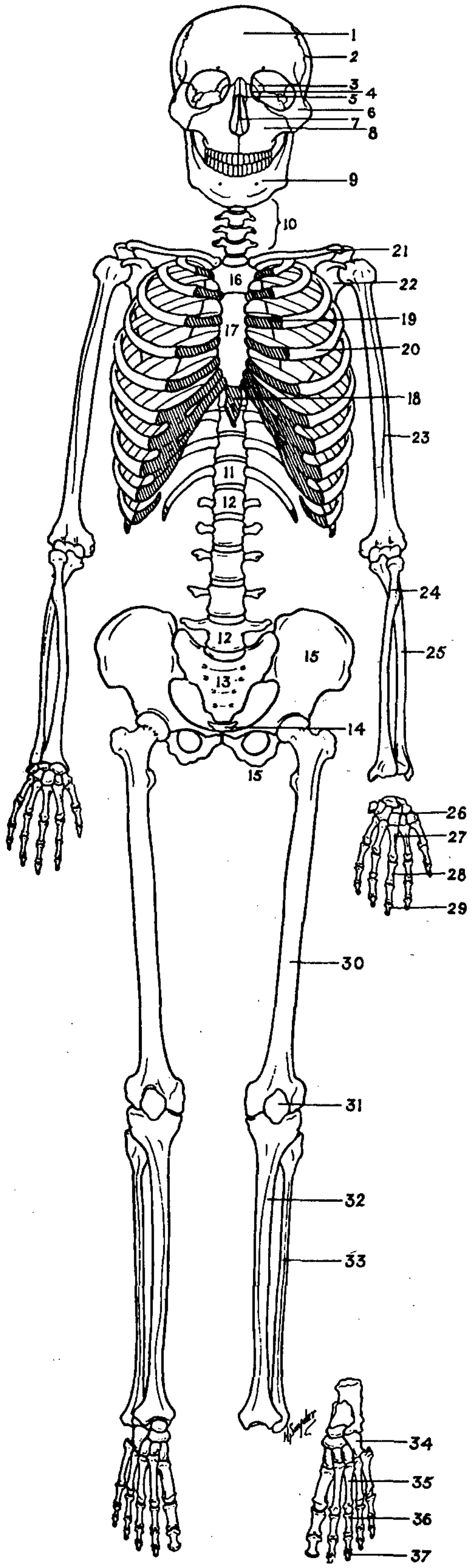
1. CEREBELLUM
2. STRAIGHT SINUS
3. QUADRIGEMINAL BODY
4. PINEAL BODY
5. MAMMILLARY BODY
6. CORPUS CALLOSUM
7. SUPERIOR SAGITTAL SINUS
8. CEREBRAL PEDUNCLE
9. PONS
10. MEDULLA OBLONGATA
11. MENINGES
12. OPTIC CHIASMA
13. FRONTAL LOBE OF BRAIN
14. FRONTAL SINUS
15. SPHENOIDAL SINUS
16. OLFACTORY BULB
17. PITUITARY BODY
18. TURBINATES
19. HARD PALATE
20. SOFT PALATE
21. TONGUE
22. TONSIL
23. TONGUE
24. HYOID BONE
25. EPIGLOTTIS
26. OESOPHAGUS
27. INTERVERTEBRAL DISC
28. THYROID CARTILAGE
29. TRACHEA
30. CEREBRAL ARTERIES
31. SPINAL CORD
32. SUBARACHNOID SPACE

FIGURE 31 MEDIAN HEAD SECTION



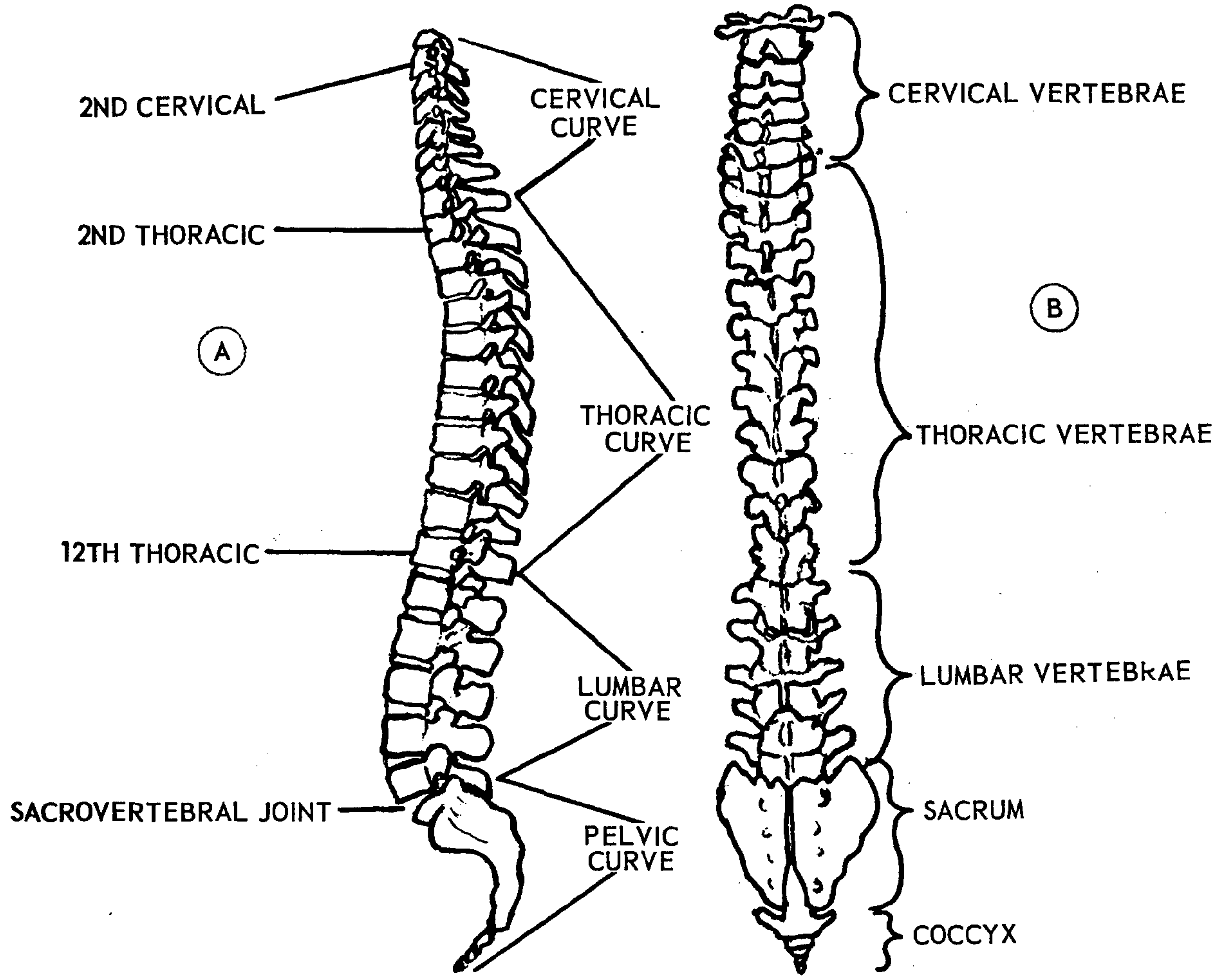
A. SECTION OF EYEBALL
B. MUSCLES OF EYE
1. CRYSTALLINE LENS
2. IRIS
3. CORNEA
4. ANTERIOR CHAMBER (CONTAINS AQUEOUS HUMOR)
5. POSTERIOR CHAMBER (CONTAINS AQUEOUS HUMOR)
6. CONJUNCTIVA
7. VITREOUS HUMOR
8. CILIARY MUSCLE
9. SUSPENSORY LIGAMENT OF THE LENS
10. SCLERA
11. CHOROID
12. RETINA
13. M. RECTUS MEDIALIS
14. M. RECTUS LATERALIS
14a. UPPER HEAD OF RECTUS LATERALIS
14b. LOWER HEAD OF RECTUS LATERALIS
15. VORTEX VEIN
16. CENTER LINE OF VISION
17. OPTIC AXIS
18. CENTRAL FOVEA (MACULA LUTEA, THE YELLOW SPOT OF MAXIMUM VISION)
19. OPTIC NERVE
20. EXCAVATION OF OPTIC NERVE - THE BLIND SPOT
21. M. RECTUS INFERIOR
22. M. OBLIQUUS INFERIOR
23. PULLEY
24. SUPERIOR TARSUS
25. M. LEVATOR PALPEBRAE SUPERIOR
26. M. OBLIQUUS SUPERIOR
27. M. RECTUS SUPERIOR

FIGURE 32 THE HUMAN EYE

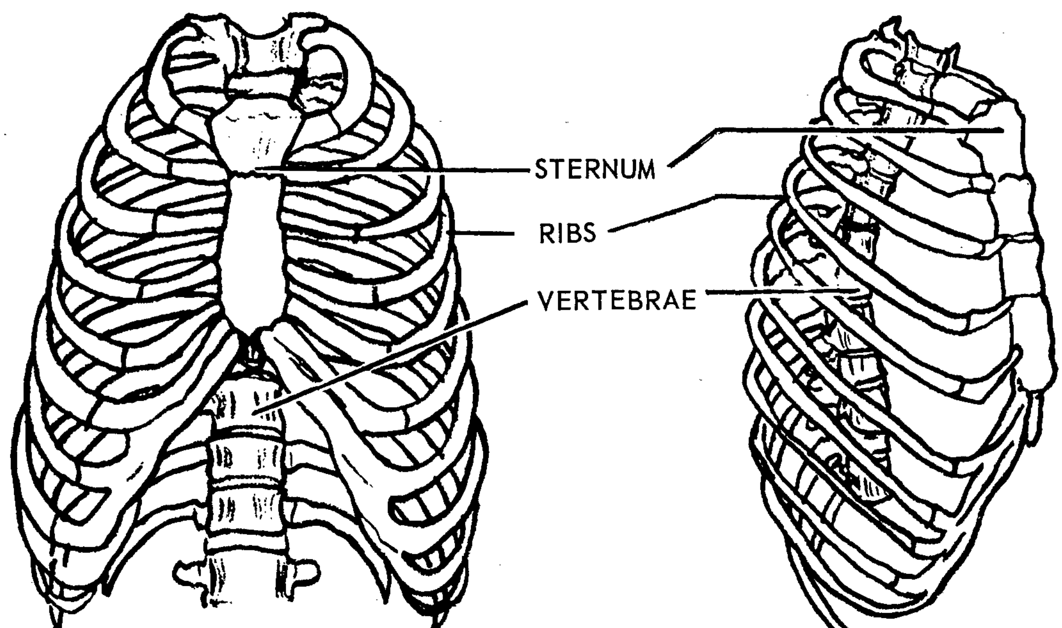


1. FRONTAL
2. PARIETAL
3. ETHMOID
4. LACRIMAL
5. NASAL
6. ZYGOMATIC, OR MALAR
7. VOMER
8. MAXILLA
9. MANDIBLE
10. CERVICAL VERTEBRAE (7)
11. THORACIC VERTEBRAE (12)
12. LUMBAR VERTEBRAE (5)
13. SACRUM (5 VERTEBRAE)
14. COCCYX (4VERTEBRAE)
15. PELVIS
16. MANUBRIUM OR PRESTERNUM
17. MESOSTERNUM, OR BODY OF STERNUM
18. XIPHOID PROCESS
19. COSTAL CARTILAGES
20. RIBS, 12 PAIRS
21. CLAVICLE
22. SCAPULA
23. HUMERUS
24. RADIUS
25. ULNA
26. CARPALS
27. METACARPALS
28. PHALANGES
29. DIGITS
30. FEMUR
31. PATELLA
32. TIBIA
33. FIBULA
34. TARSALS
35. METATARSALS
36. PHALANGES
37. DIGITS

FIGURE 33 HUMAN SKELETON ENTIRE

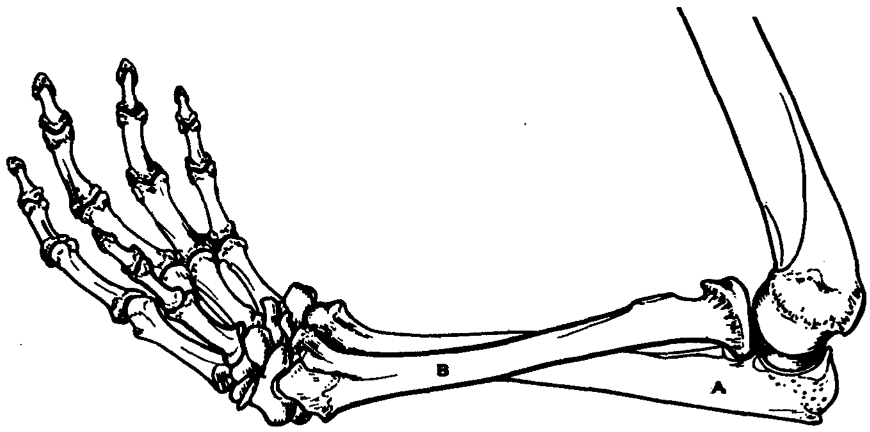


A, RIGHT LATERAL VIEW SHOWING CURVES; THE VERTEBRAL COLUMN. B, DORSAL VIEW

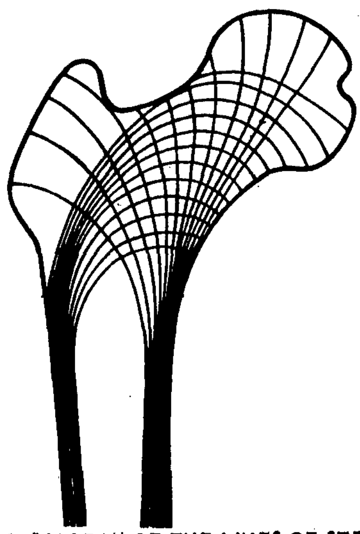


A. FRONT VIEW THORAX B. SIDE VIEW

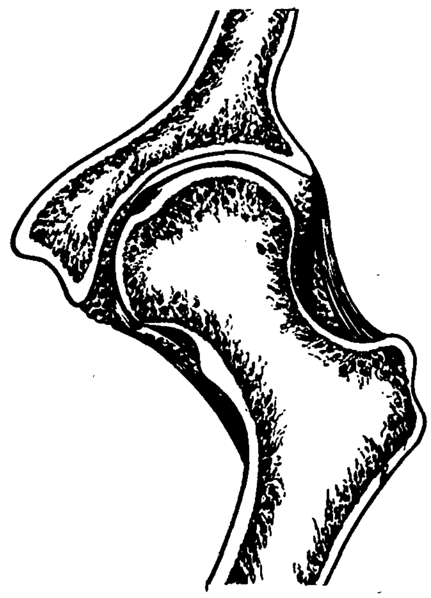
FIGURE 34 SKELETAL DETAILS



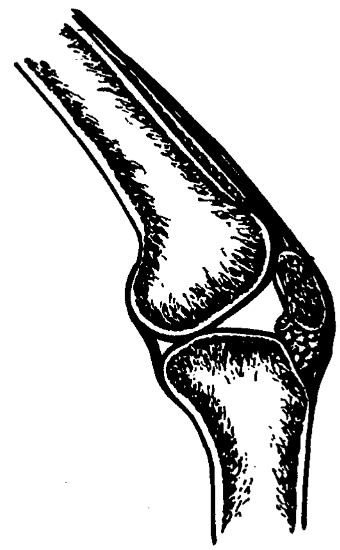
1. ROTATING JOINT OF FOREARM AND WRIST. IN THIS JOINT TWO TYPES OF MOTION ARE FOUND: THE MOVEMENT OF THE TWO LONG BONES OF THE ARM, ULNA (A) AND RADIUS (B). THE ULNA (A) WHICH ARTICULATES WITH THE HUMERUS HAS AN UP AND DOWN MOVEMENT IN A FIXED POSITION, WHILE THE RADIUS (B) ROTATES ON THE ULNA (A). THE WRIST BONES MOVE ON THE EXTREMITY OF THE RADIUS IN EITHER OF THE TWO PLANES.



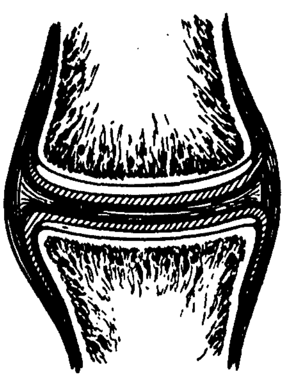
2. DIAGRAM OF THE LINES OF STRESS IN THE HEAD OF THE FEMUR. THE ARROW INDICATES THE POINT AT WHICH THE FORCE CENTERS.



3. BALL AND SOCKET JOINT OF THE HIP. THE BALL-SHAPED HEAD OF THE FEMUR ROTATES IN THE CUP-SHAPED SOCKET IN THE PELVIS.



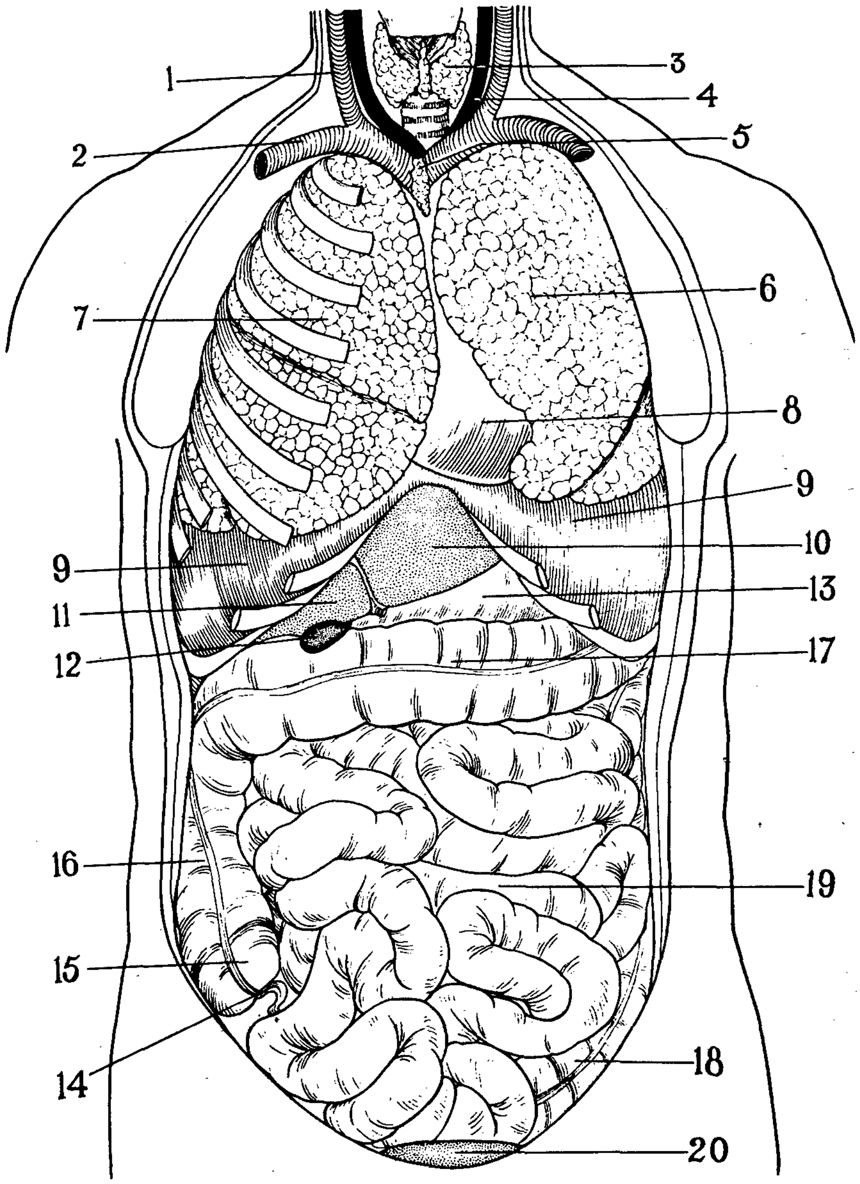
4. HINGE JOINT OF THE KNEE, THIS TYPE OF JOINT MOVES BACKWARD AND FORWARD IN ONE PLANE. THE PATELLA, A BONE FORMED IN THE LIGAMENT, PROTECTS THIS JOINT



5. GLIDING JOINT, FOUND BETWEEN THE BONES OF WRIST AND OF THE ANKLE, AND BETWEEN THE VERTEBRAE. THE BONES SLIDE OVER EACH OTHER THROUGH A NARROW RANGE, AND SUCH JOINTS ARE VERY STRONG.

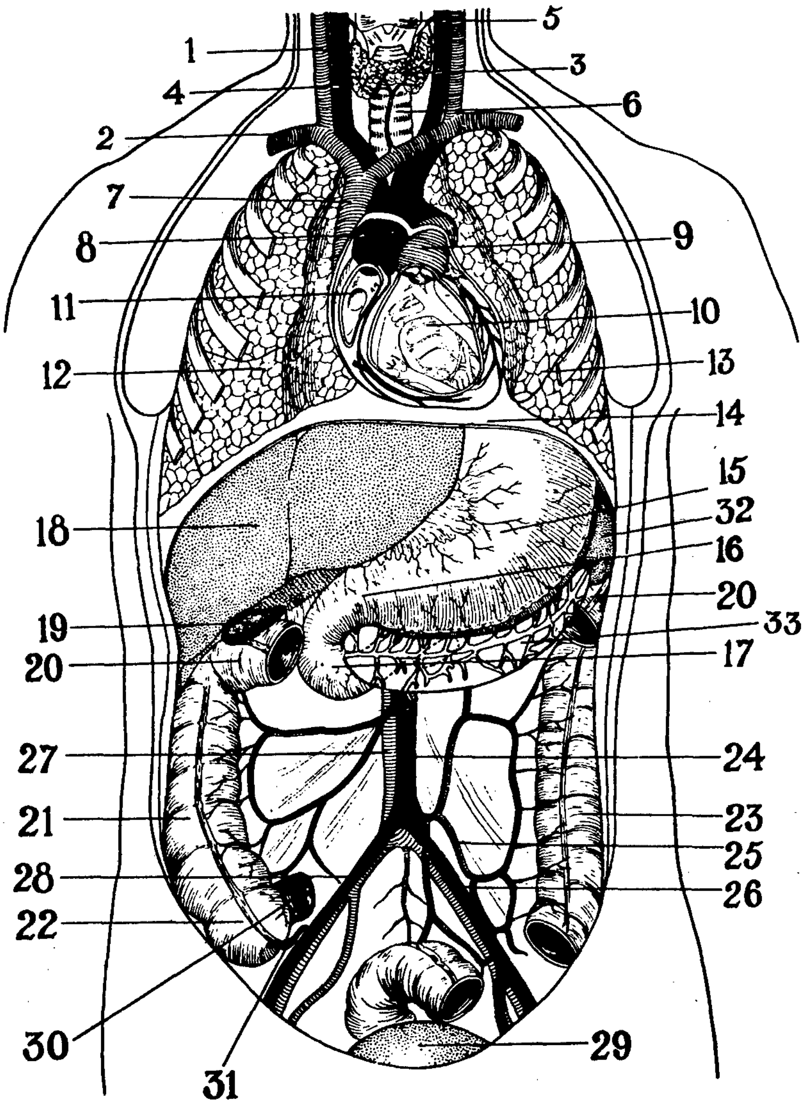
6. THE ARCH OF THE FOOT, MADE UP OF BONES WITH GLIDING JOINTS, SUPPORTS WEIGHT OF THE BODY.

FIGURE 35 JOINT ARTICULATION



1. INTERNAL JUGULAR VEIN
2. SUBCLAVIAN VEIN
3. THYROID GLAND
4. COMMON CAROTID ARTERY
5. THYMIC REMNANT
6. LEFT LUNG
7. RIGHT LUNG
8. PERICARDIUM
9. DIAPHRAGM
10. LEFT LOBE OF LIVER
11. RIGHT LOBE OF LIVER
12. GALL BLADDER
13. STOMACH
14. APPENDIX
15. CECUM
16. ASCENDING COLON
17. TRANSVERSE COLON
18. DESCENDING COLON
19. COILS OF SMALL INTESTINE
20. URINARY BLADDER

FIGURE 36 VISCERA OF CHEST AND ABDOMEN (FIRST LAYER)



1. INTERNAL JUGULAR VEIN
2. SUBCLAVIAN VEIN
3. THYROID GLAND
4. COMMON CAROTID ARTERY
5. THYROID CARTILAGE
6. TRACHEA
7. SUPERIOR VENA CAVA
8. ASCENDING AORTA
9. PULMONARY ARTERY
10. RIGHT VENTRICLE
11. RIGHT AURICLE
12. RIGHT LUNG
13. LEFT LUNG
14. DIAPHRAGM
15. STOMACH
16. PYLORUS
17. DUODENUM
18. LIVER
19. GALL BLADDER
20. TRANSVERSE COLON
21. ASCENDING COLON
22. CECUM
23. DESCENDING COLON
24. AORTA
25. INFERIOR MESENTERIC ARTERIES AND VEINS
26. LEFT COMMON ILIAC ARTERY AND VEIN
27. INFERIOR VENA CAVA
28. RIGHT COMMON ILIAC ARTERY AND VEIN
29. URINARY BLADDER
30. ILEOCECAL VALVE
31. APPENDIX
32. SPLEEN
33. PANCREAS

FIGURE 37 VISCERA OF CHEST AND ABDOMEN (SECOND LAYER)

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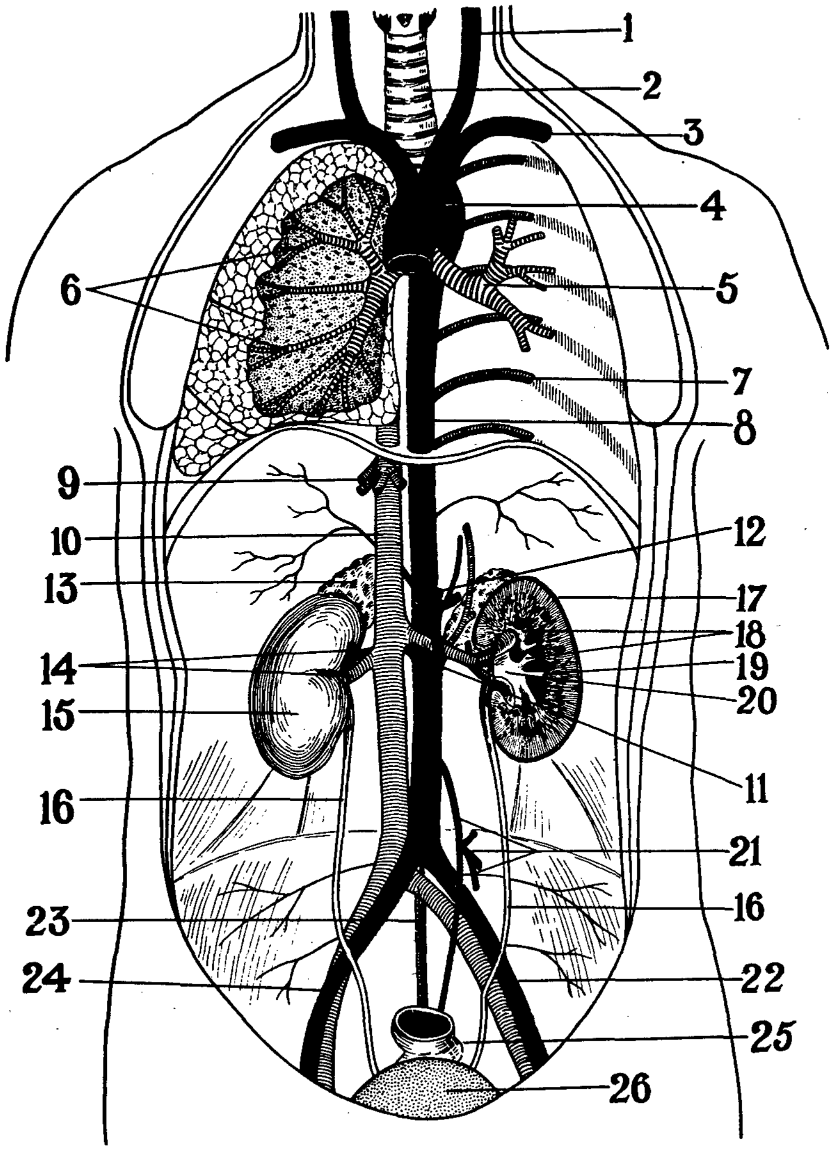
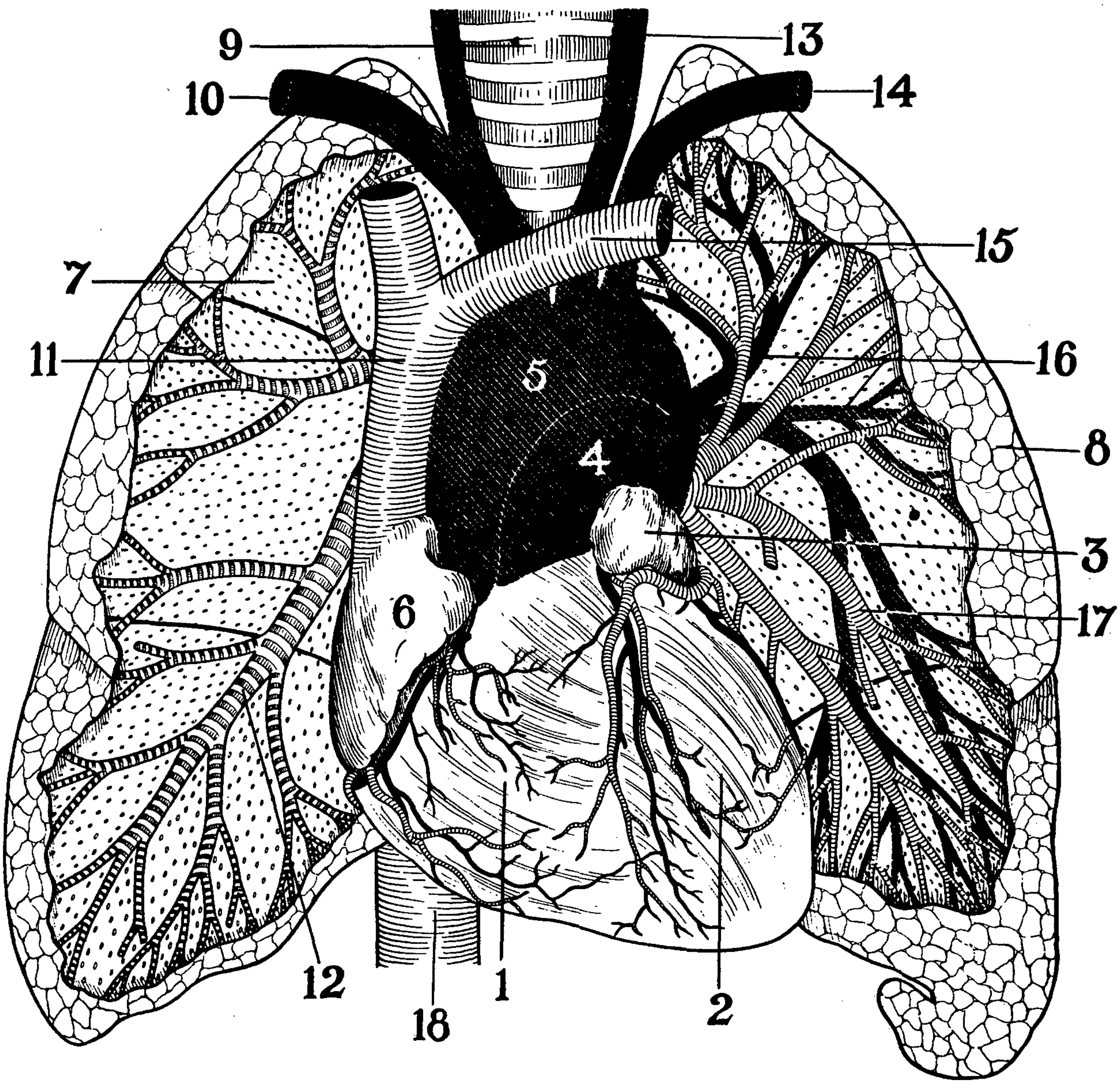


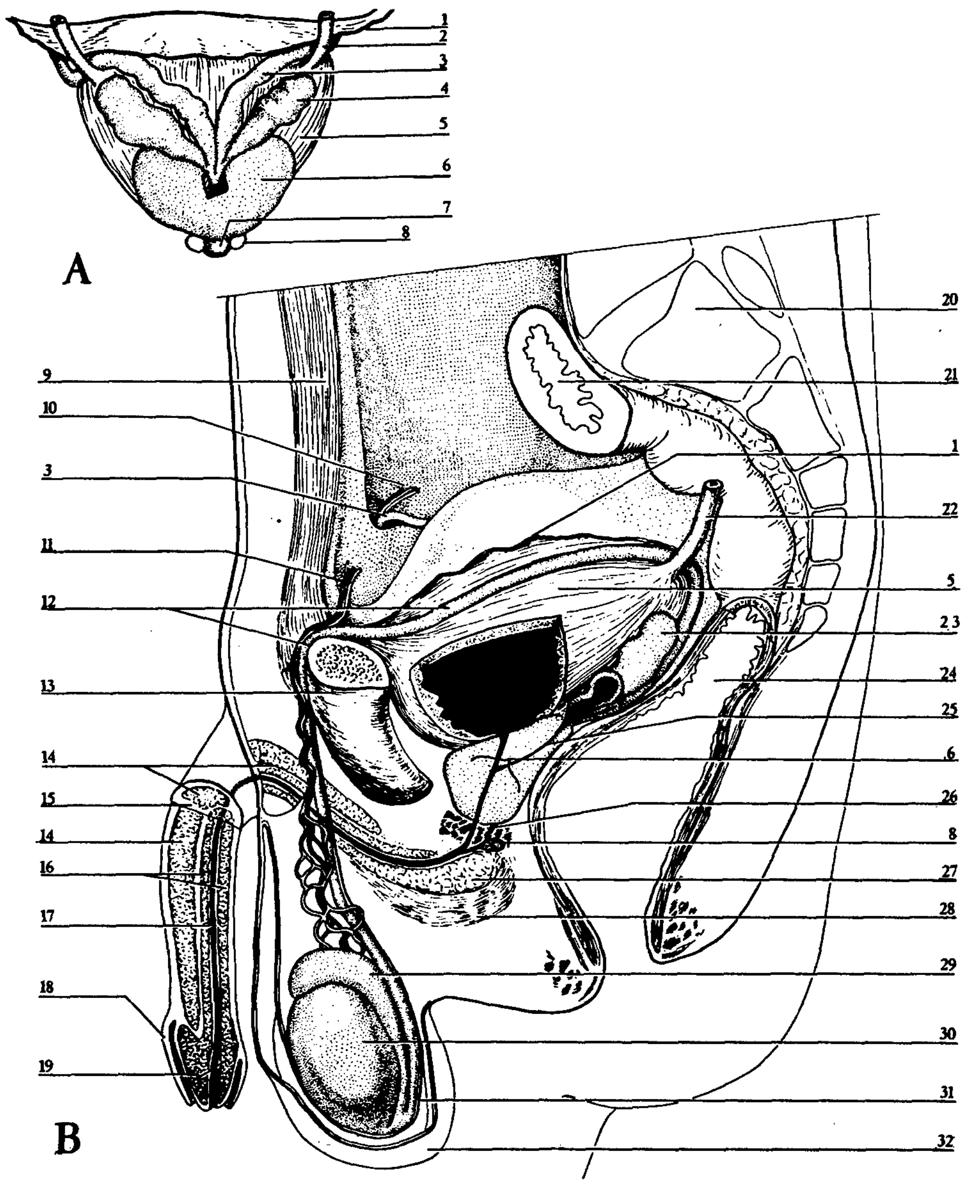
1. COMMON CAROTID ARTERY
2. TRACHEA
3. SUBCLAVIAN ARTERY
4. AORTIC ARCH
5. LEFT BRONCHUS
6. RIGHT MINOR BRONCHI
7. INTERCOSTAL BLOOD VESSELS
8. DESCENDING AORTA
9. HEPATIC VEINS
10. INFERIOR VENA CAVA
11. SUPERIOR MESENTERIC ARTERY
12. COELIAC ARTERY
13. RIGHT ADRENAL GLAND
14. RENAL BLOOD VESSELS
15. RIGHT KIDNEY
16. URETER
17. LEFT KIDNEY DISSECTED
18. CALICES
19. PYRAMID
20. PELVIS
21. INFERIOR MESENTERIC ARTERY
22. LEFT COMMON ILIAC
23. MIDDLE SACRAL ARTERY AND VEIN
24. RIGHT COMMON ILIAC
25. COLON
26. BLADDER

FIGURE 38 VISCERA OF CHEST AND ABDOMEN (THIRD LAYER)



1. RIGHT VENTRICLE
2. LEFT VENTRICLE
3. LEFT AURICLE
4. PULMONARY ARTERY
5. ARCH OF AORTA
6. RIGHT AURICLE AND ATRIUM
7. RIGHT LUNG
8. LEFT LUNG
9. TRACHEA
10. RIGHT SUBCLAVIAN ARTERY
11. SUPERIOR VENA CAVA
12. BRONCHUS
13. LEFT COMMON CAROTID ARTERY
14. LEFT SUBCLAVIAN ARTERY
15. LEFT INNOMINATE VEIN
16. PULMONARY ARTERIES
17. PULMONARY VEINS
18. INFERIOR VENA CAVA

FIGURE 39 HEART AND LUNGS



A. BLADDER, VASA DEFERENTIA, SEMINAL VESICLES AND PROSTATE VIEWED FROM BEHIND

B. LEFT LATERAL DISSECTION WITH LEFT TESTIS AND LEFT VAS DEFERENS SUPERIMPOSED : AND PARTS OF BLADDER, SEMINAL VESICLE AND VAS DEFERENS CUT. PROSTATE SHOWN TRANSPARENT.

1. PERITONEUM
2. RIGHT URETER
3. RIGHT VAS DEFERENS
4. RIGHT SEMINAL VESICLE
5. URINARY BLADDER
6. PROSTATE GLAND
7. MEMBRANOUS URETHRA
8. BULBO-URETHRAL GLAND (COWPER'S GLAND)
9. RECTUS ABDOMINIS MUSCLE
10. RIGHT SPERMATIC VEINS AND ARTERY
11. LEFT SPERMATIC VEINS AND ARTERY
12. LEFT VAS DEFERENS
13. PUBIS (CUT AWAY)
14. CORPORA CAVERNOSA OF PENIS
15. SEPTUM OF PENIS
16. CORPUS CAVERNOSUM OF URETHRA
17. URETHRA
18. PREPUCE
19. GLANS PENIS
20. SACRAL VERTEBRAE
21. PELVIC COLON
22. LEFT URETER
23. LEFT SEMINAL VESICLE
24. RECTUM (CUT OPEN)
25. EJACULATORY DUCT
26. SPHINCTER OF URETHRA
27. BULB OF PENIS
28. BULBO-CAVERNOSUS MUSCLE
29. EPIDIDYMIS
30. TESTIS
31. TUNICA VAGINALIS
32. SCROTUM

FIGURE 40 REPRODUCTIVE ORGANS

TABLE II

SURVEY OF INJURIES

BODY SEGMENT	DIRECTION	PEAK G	DURATION SEC	RATE OF ONSET G/SEC	RESTRAINT APPLIED TO SEGMENT
Ref. 60		Operational Ejection (510 knots)			Std. USAF Harness and positioning
Ref. 60		Operational Ejection (550 knots)			
Whole Man Age 27 Ht. 5'7" Wt. 140# Ref. 19	Semi-supine	Unknown	Unknown	From 14th floor. Fell 146' onto top and rear of deck of a coupe. Velocity at contact was 86'/sec	No restraint; free fall
Whole Woman: Ref. 19	Steamer-chair position	100 avg.	Unknown	From 17th floor. Fell 144' onto metal ventilator box	No restraint; free fall
Whole Man Ref. 19	Tumbled	191	Unknown	Fell 320' onto beach (160' fall to ledge 160' fall to beach) Velocity on beach, 65 mph	No restraint; free fall

INJURY OR COMMENT	PROVISIONS RECOMMENDED TO EXTEND MAN'S TOLERANCE OR REASONING EMPLOYED IN RECOGNITION OF INHERENT TOLERANCE
Separation of symphysis pubis. Open shock of chute	Lateral support around pelvis and broad support over lower torso.
Dislocation of atlanto-occipital joint with compression of spinal cord, retroperitoneal hemorrhage and other trauma. Probable extreme opening shock at extremely high speed while still in seat.	Head restraint to prevent dynamic respone of head. Proper automatic body and head positioning.
Compound comminuted of the left elbow. Impact fracture of head and neck of left humerus. Comminuted fracture through spine of left scapula. Compression fracture of 7th and 8th dorsal vertebrae. Fracture of base of greater tuberosity of ischium. Moderate shock but conscious. No chest or head injuries. During 1st week abdomen was distended, patient vomited, internal injuries; 2nd week, jaundice developed. Recovery was uneventful. Returned to work 2 months later when arm was healed.	Not Applicable
She remembers falling and landing. No marks on head or loss of consciousness. Sat up and asked to be taken to her room. Fractures of both bones of both forearms, left humerus and extensive injuries to left foot. No evidence of abdominal or intrathoracic injury.	Not Applicable.
Skin tear on right knee. Scalp lacerations. No fracture of long bones. No intrathoracic or abdominal injury. Fissured fracture of skull. Unconscious for 3 days.	Not Applicable.

TABLE II (Cont'd)

SURVEY OF INJURIES

BODY SEGMENT	DIRECTION	PEAK G	DURATION SEC	RATE OF ONSET G/SEC	RESTRAINT APPLIED TO SEGMENT
Whole Woman: Age 30 Ht. 5'6" Wt. 122# Ref. 19	Face downward, prone	Unknown	Unknown	From 9th floor. Fell 74' onto an iron bar, metal screens, a skylight of wired glass, metal lath ceiling 66'/sec	No restraint; free fall
Whole Body: Ref. 19	Face downward	Unknown	Unknown	Fell 100' onto a screen with iron supports over a skylight	No restraint; free fall
Whole Woman: Age 21 Ht. 5'7" Wt. 115# Ref. 19	Supine, right side and back	166	Unknown	From 10th floor. Decelerative distance max. 6". Velocity at contact 73'/sec. Flower bed. Freshly turned earth.	No restraint; free fall
Whole Man Age 42 Ref. 19	Face downward	100-200	Unknown	From 10th floor. Fell 108' onto hood and fenders of auto. Decelerative distance varied from 6" to 12", 79'/sec	No restraint; free fall
Whole Body: Ref. 19	Face downward	Unknown	Unknown	Fell 134' onto hood and fenders of demolished car. Bounced from car to 3'; landed head down on pavement after 5' fall	No restraint; free fall

INJURY OR COMMENT	PROVISIONS RECOMMENDED TO EXTEND MAN'S TOLERANCE OR REASONING EMPLOYED IN RECOGNITION OF INHERENT TOLERANCE
Minor patterned contusions. "H"-shaped laceration on forehead from screen wires. All other injuries were minor except in thoracic area-marked tenderness of the upper ribs on right side near anterior axillary line, with slight crepitus. Fractures of the 4th, 5th, and 6th rib on right side. No loss of consciousness. Moderate shock.	Not Applicable
Fracture of 7th, 8th, and 9th rib on right side. Right pneumothorax and subcutaneous emphysema. Moderate shock. No head injuries. Recovery was uneventful.	Not Applicable
Fractured a rib on right side. Fractured right wrist. No loss of consciousness. No concussion.	Not Applicable
Frontal fracture of skull (he bounced from car to pavement). No loss of consciousness.	Not Applicable
No material facial injuries. Only brief loss of consciousness. Frontal scalp lacerations, severe shearing stress in upper portion of abdomen. No intrathoracic injury. Died 24 hours after accident as a result of shock. No rupture of major internal organs was revealed at autopsy.	Not Applicable

TABLE II (Cont'd)

SURVEY OF INJURIES

BODY SEGMENT	DIRECTION	PEAK G	DURATION SEC	RATE OF ONSET G/SEC	RESTRAINT APPLIED TO SEGMENT
Leg: Ref. 77	$-G_x$	50	0.045	1300	Effectively none
Ref. 60	Tumbled		Operational Ejection		Positioning only
Ref. 60	Tumbled		Operational Ejection		Positioning only
Arm: Ref. 60	Tumbled		Operational Ejection		Armrest
Ref. 60	Tumbled		Operational Ejection		Armrest
*Live Pig: (Whole Body)	Five Degree, nose up. Inverted prone posture.				Form-fitting mold secured with straps
Subj. 3: Thorax *	5^o Nose up; supine	63		9600	Form-fitting mold secured with straps
Abdomen *	5^o Nose up; supine	60		5200	Form-fitting mold secured with straps
Subj. 4: Thorax *	5^o Nose up; supine	44		5300	Form-fitting mold secured with straps
Abdomen *	5^o Nose up; supine	54		4600	Form-fitting mold secured with straps

*Brock, F. J., Acceleration Shock Protection Experiments Using Live Pigs, McDonnell Aircraft Corp., St. Louis, Missouri.

INJURY OR COMMENT	PROVISIONS RECOMMENDED TO EXTEND MAN'S TOLERANCE OR REASONING EMPLOYED IN RECOGNITION OF INHERENT TOLERANCE
Dislocation or strain of hip joint.	Lateral restraint of thighs incorporating additional structural support by partially encompassing greater tronchanter.
Internal derangement, left knee.	Fixing leg and foot to seat.
Traumatic amputation lower left leg. Expired 7 days after accident due to pulmonary embolism.	Fixing leg and foot to seat.
Amputation of left lower arm.	Fix arm to armrest.
Laceration both elbows.	Fix arm to armrest.
Hemorrhagic phenomena involving thoracic organs, primarily lungs, apparently attributable to trauma induced by impact against bony prominence of thorax. Rendered senseless on impact.	Broad torso restraint which prevents deformation of the thorax and distention of the abdomen. Mechanical device to prevent upward displacement of viscera by application against abdomen at waist. Note: May be involved with inherent physiology of pig. Some sources state that pig cannot tolerate the supine position with hemorrhage involving the thorax.
Not rendered senseless.	

TABLE II (Cont'd)

SURVEY OF INJURIES

BODY SEGMENT	DIRECTION	PEAK G	DURATION SEC	RATE OF ONSET G/SEC	RESTRAINT APPLIED TO SEGMENT
Black Bear No. 3, Male: Age 2 Wt. 127# Ref. 17	$+G_z$	27.7	.045		Full harness with inverted V leg straps
Whole Woman: Age 42 Ht. 5'2" Wt. 125#	Left side and back	Average 140	Unknown	From 6th floor. Fell 55' onto firmly packed earth. Deceleration distance 4". Velocity at contact was 54'/sec	No restraint; free fall
Whole Woman: Age 27 Ht. 5'3" Wt. 120# Ref. 19	Head-first; contact shoulder and back	Unknown	Unknown	From 7th floor. Fell 66' onto a wooden roof. Velocity at contact 60'/sec	No restraint; free fall
Whole Man Ref. 19	Supine position	Excess of 200	Unknown	From 14th floor. Fell 121' onto roof. Right arm struck beam and stopped abruptly. Torso continued in movement.	No restraint; free fall
Whole Woman: Age 36 Ht. 5'4" Wt. 115# Ref. 19	Face downward	Unknown	Unknown	From 8th floor. Fell 72' onto fence face downward; velocity at contact 65'/sec	No restraint; free fall

INJURY OR COMMENT	PROVISIONS RECOMMENDED TO EXTEND MAN'S TOLERANCE OR REASONING EMPLOYED IN RECOGNITION OF INHERENT TOLERANCE
Hemorrhage and edema in the gluteus medius and surrounding muscles associated with the trochanter major of the left femur.	Contour seat, tight application of restraint.
No evidence of material injuries or shock. No blood in cerebrospinal fluid. No red cells in the urine. No loss of consciousness or abdominal tenderness.	Not Applicable
Scalp lacerated (occiput) no evidence of other head injuries. Abrasions over dorsal portion of spine. Oblique intra-articular fracture of the 6th cervical vertebra. Some spasticity of the abdominal muscles on right side. Urinalysis yielded normal results. Evidence of mild shock.	Not Applicable
Walked away from spot where he landed. Tearing action in the shoulder area. Other injuries. Death attributed to severance of brachial arteries, hemorrhage and shock. No head injury or loss of consciousness	Not Applicable
No evidence of material injury.	Not Applicable

TABLE II (Cont'd)

SURVEY OF INJURIES

BODY SEGMENT	DIRECTION	PEAK G	DURATION SEC	RATE OF ONSET G/SEC	RESTRAINT APPLIED TO SEGMENT
Chimpanzee:					
Ref. 79 Whole Body:	$+G_y$ Run 185	30	0.118	1,000	Triangular shape nylon-netting harness
Whole Body:	$+G_y$ Run 186	47	0.140	1,168	Triangular shape nylon-netting harness
Whole Body:	$-G_x$ Run 83	40		1,000	M-16 shoulder strap and G lap belt (the harness did not fit tightly)
Whole Body:	$+G_x$ Run 170	35		2,000	Chest belt and lap belt
Whole Body:	$+G_z$	30		1,000	3" webbing arranged like parachute harness
Black Bear No. 1, Male: Age 2 Wt. 143# Ref. 17	$-G_y$	25	0.24		Std. USAF Restraint harness with inverted V leg straps

INJURY OR COMMENT	PROVISIONS RECOMMENDED TO EXTEND MAN'S TOLERANCE OR REASONING EMPLOYED IN RECOGNITION OF INHERENT TOLERANCE
No injuries. No muscle soreness.	
Unknown.	
Pale, trembling, helpless and in shock. Two lacerations into the skin of shoulders. He remained lethargic and prostrated for an hour.	Tight application of torso restraint device to prevent dynamic response within restraint harness and also to prevent rebound. Restraint of head to prevent dynamic response of the head and possible whip-lash injury to neck and shock. The latter by reduction of hemodynamic pressure.
Stunned. No evidence of injuries other than the disoriented comatose immediately after deceleration.	Broad distribution of force over head and shock adsorption.
No injuries.	
Hemorrhage in and about tunica adventitia of both phrenic arteries and veins. Displacement of the diaphragm upward by abdominal viscera. Tearing of soft tissues about and involving the vessel walls with resulting hemorrhage. Minimal and entirely reversible lesions.	Broad torsion restraint which prevents deformation of abdomen and thorax.

TABLE II (Cont'd)

SURVEY OF INJURIES

BODY SEGMENT	DIRECTION	PEAK G	DURATION SEC	RATE OF ONSET G/SEC	RESTRAINT APPLIED TO SEGMENT
Black Bear No. 2, Male: Age 2 Wt. 137# Ref. 17	$+G_z$	59	0.026		Full harness with inverted V leg straps
Head: Ref. 8	$+G_x$	83+	0.04	3,800	Flat rigid plate covered by 1/2" felt
Ref. 48	Tumbled	64-35	0.120	700	None
Ref. 77	$-G_x$	45+	0.044	500	Lap belt, shoulder harness with chest strap. Helmet (Std. USAF 4#s).
Ref. 60	Tumbled		Operational Ejection		Helmet and positioning
Ref. 60	Tumbled		Operational Ejection		Helmet and positioning
Torso: Ref. 8	$+G_x$	83	0.045	3,800	Rigid steel plate covered 1/2" felt
Ref. 48	$-G_x$	50	0.045	1,300	None

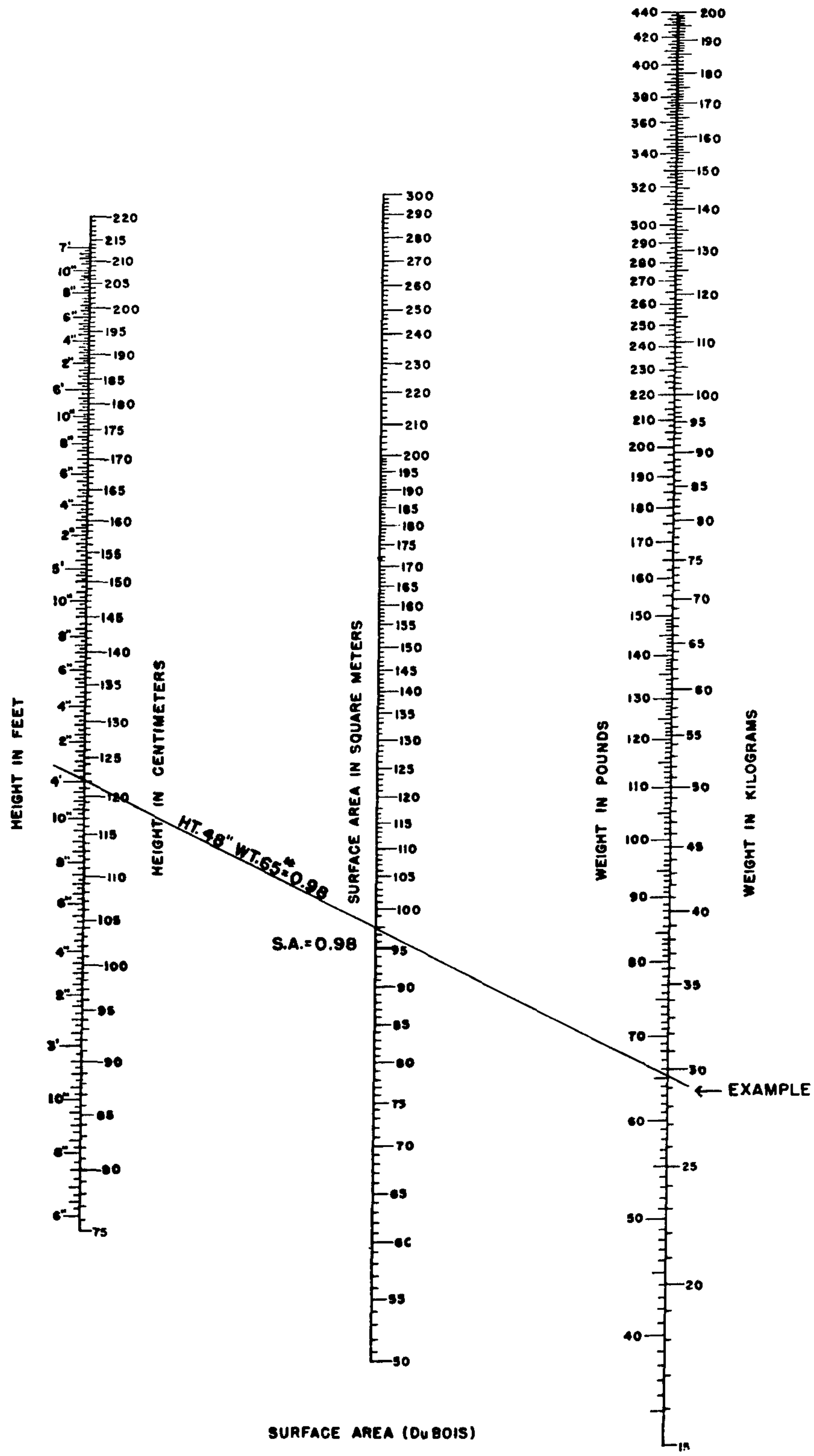
INJURY OR COMMENT	PROVISIONS RECOMMENDED TO EXTEND MAN'S TOLERANCE OR REASONING EMPLOYED IN RECOGNITION OF INHERENT TOLERANCE
Capsular tears and hemorrhages dorsal portion, and small multiple subcapsular hemorrhages ventral portion right lobe, liver. Hemorrhages, psoas muscles, bilateral second and third lumbar vertebrae levels. Fracture, overriding second caudal vertebra. Hemorrhage and edema, bilateral subcutis and skeletal muscles at lumbar vertebrae 1, and 2 level.	Visceral restraint by interruption at the waist and full encapsulation.
Transitory unconsciousness. Neck pain.	Distribution of force over whole skull surface. (Beeding-Daisy decelerator.)
Subconjuntival hemorrhages, face swollen, blue; deep circulator shock; blood behind tympanic membranes. Concussion (mild). (Head covered by helmet.)	Head restrained over broad surface area, restrained in all directions. Broad application of restraining supports Fixed restraint to prevent head whip.
Retinal hemorrhage. Mild shock.	Head restraint to prevent head-whip and resulting increase in blood pressure in the head. Broad application of restraint support.
Surface wounds, head.	Head support device should follow head movement.
Bilateral subscleral hemorrhage and hemorrhage, purpura.	Face shield or escape capsule.
Postulate minor hemorrhage in abdomen based on RBC in urine.	Encapsulation of torso to maintain normal shape and reduce visceral and organ displacements.
Bruises under arm and groin. Stomach distended indicated high force application, probably by lap belt. Intra-abdominal and retroperitoneal hemorrhages. Liver damage indicated by jaundice. Intestinal tearing.	Same as above. Reorientation of restraint forces over wide areas with low specific load. Attachment achieved without concentration of force.

TABLE II (Cont'd)

SURVEY OF INJURIES

BODY SEGMENT	DIRECTION	PEAK G	DURATION SEC	RATE OF ONSET G/SEC	RESTRAINT APPLIED TO SEGMENT
Whole Body: Ref. 60				Operational Ejection (500 - 580 knots I.S.A.)	Std. USAF harness and positioning
Ref. 60				Operational Ejection (500 knots I.S.A.)	Std. USAF harness and positioning

INJURY OR COMMENT	PROVISIONS RECOMMENDED TO EXTEND MAN'S TOLERANCE OR REASONING EMPLOYED IN RECOGNITION OF INHERENT TOLERANCE
Compression fractures, lower thoracic (1 vert.) and upper lumbar vertebrae (2 vert.), caused by ejection force when body improperly positioned.	Automatic positioning of body in proper vertebral alignment.
Sub-conjunctival and intra-ocular hemorrhage. Hepatic laceration. Cerebral concussion caused by deceleration due to resistance of air.	Wind screen or capsule, automatic body positioning, broad support. Head restraint.



Place a ruler over the proper height and weight. Read off the surface area at the point the ruler crosses the middle line.

FIGURE 41 ESTIMATION OF SURFACE AREA OF THE BODY

APPENDIX II
A CONCEPT FOR ESTIMATING LIMIT HUMAN TOLERANCE TO IMPACT ACCELERATION

A. B. Thompson

Acceleration, being a critical parameter in aircraft long before these days of manned space flight, is probably one of the most researched and yet one of the least exactly defined stresses on man with which design engineers must contend. Confusion has existed among many crew station designers even as to the terminology for acceleration and its resulting inertial effect, G. A significant step toward alleviating this communication problem between the medical and engineering doctrines was the acceptance by the Acceleration Committee, Panel of Aerospace Medicine, AGARD, NATO, and the Life Sciences Committee of the Aerospace Medical Association of a common Table of Equivalent Acceleration Terminologies (A1). Recently mathematical techniques and specialized electronic analog computers have been developed by Payne (A2, A3) and others whereby restraint system dynamic performance, including man's mechanical response to impact acceleration, can be predicted prior to actual system fabrication. Lacking, however, is a reliable method to predict an individual's physiological tolerance limit to the impact force.

The results of acceleration acting on the human have been expressed in terms of such varied parameters as the magnitude of the acceleration, its duration, its direction relative to the axes of the body, the delta change of velocity of the body mass, the rate of onset of the acceleration, the onset time, etc. Which variables are dependent and which are independent, and have all independent variables been considered? There has been a relatively large amount of literature published concerning man's tolerance to rapidly applied accelerative stresses, but few useful quantitative values have been established. This is a common fault in many areas of biological experimentation when the human is the object of study. The recorded data have many discrepancies because of inherent individual differences in the subjects used. Thus, when the basic individual differences are combined with the variations in the experimental techniques, the results become rather difficult to interpret and/or correlate with any degree of confidence.

Most authorities agree that if the duration of the acceleration is sufficiently short, the human body should be considered purely from its structural strength aspect because virtually no relative fluid shift takes place. The tissues of the body yield largely to structural damage or failure as a result of the application of mechanical force, reacting like inert materials under conditions of mechanical stress. The location of internal injuries does not necessarily bear a direct relationship to the location of application of the force. Some of the injuries may result from the "plastic" internal organs and particular fluid elements. It is known, too, that when the whole body is subjected to rapidly applied accelerations the internal organs relative to the fixed bony structure become mobile and cause shearing stresses (A4). The viscoelastic properties of tissues also play a part in determining the total effect. When reversible limits of these properties have been exceeded, structural failure occurs and injury or death may result.

Most experimental work in the field of acceleration has been recorded as peak G tolerated versus time. Figure 42 is a plot of major experimental findings for the transverse anterior-posterior and posterior-anterior orientation of G force over a large time spectrum (source references A5 through A19). The data above 2.0 seconds in time is from centrifuge studies, from .1 second to 1.0 second is from high-speed sleds, .03 second to .1 second is from short-track impact facilities, and below .03 seconds from drop towers and falls. Of interest in the impact region is a change of slope of the maximum tolerance limit occurring at .07 seconds. Below this time limit, it is presumed the body reacts as a rigid unit mass and structural damage and failure is independent of displacement effects in respect to gradients of fluid displacement or deformation of tissue. By definition then, impact accelerations will be those accelerations lasting less than .07 seconds in time.

M. Kornhauser has adapted a form of presentation (A20), used by the U. S. Naval Ordnance Laboratory to describe inertia mechanism response, to describe human impact tolerance, viz., a plot of the parameter of velocity change versus G. The hypothesis is that below a certain $\Delta \overline{V}$ no damage for any G application will result. As decelerations in this short time of impact are very nearly triangular or sine-type pulses, the $\Delta \overline{V}$ versus G relationship -- in order to be consistent with the data of Figure 42 -- should be:

$$\Delta \overline{V} = \frac{G_{peak}}{2} \, g_o \, t$$

or:

$$2 \, \Delta \overline{V} \quad \text{versus} \quad G_{peak}$$

Data from tests and falls are plotted in this relationship in Figure 43. Of interest is the change of tolerance associated with the .07 seconds impact time consistent with Figure 42. Also, the $2\Delta\overline{V}$ tolerance value is at approximately 100 or a $\Delta\overline{V}$ of 50 feet/second for a triangular impulse. Unanswered is the question of how high a G man can tolerate at $\Delta\overline{V}$'s of 50 ft/sec. and below. It is known that various structural failures can occur in man if he impacts an unyielding surface in a fall from as low as 5 or 6 feet. National Safety Council release on urban automobile accidents indicates that 40% of fatalities were associated with speeds of less than 20 mph, or 29.5 ft/sec, and 70% of fatalities were at speeds below 30 mph, or 44 ft/sec (A21). Tests by White, et al. (A22), on animals and extrapolated to man give a $\Delta\overline{V}$ impact on unyielding surface for 50% mortality of 27 ft/sec. Apparently there is an upper limit tolerance load even at low delta velocities. From a rational analysis it appears that force per unit area may be the independent variable which will define this end of the spectrum at which structural failures occur.

White, *et al.* (A22), in "sharp"-rising overpressure blast tests on animals and extrapolated to a 165-lb man, give a 50% mortality at 45-55 psi. Analysis of sled tests indicates that onset of shock occurs at approximately 30 psi unit pressure on man; and Beeding's 82.6 G sled run gave a value of 44.6 psi unit pressure, which was approaching irreversible damage. Several sled tests, drop tests, and fall analyses (shown in Figure 44) are plotted as body pressure versus time. Thus, for any given restraint system, body-supported area projected in the impact plane, and body weight when subjected to the constraints of maximum unit pressure, delta velocity, and time define a unique human tolerance envelope for that restraint system. For example, the Vought high G restraint system has a theoretical maximum transverse peak G capability of 110 G at a $\Delta\overline{V}$ of 50 ft/sec, 45 psi unit pressure, and .028 second time. If the $\Delta\overline{V}$ is held constant and the time lengthened, the unit pressure (or G) decreases. If the unit pressure (or G) is held constant and the impact time decreased, the $\Delta\overline{V}$ is forced to decrease. Based on this analysis a normal operating impact load in the supine G direction (where the force per unit area is limited to 30 psi) for the Vought system is 73.1 G at a 50 ft/sec $\Delta\overline{V}$. This results in an impact time of .042 seconds. The same analytical procedure should produce envelopes for various restraint systems and impact orientations. Further tests in which these parameters are recorded are urged for validation of this analysis.

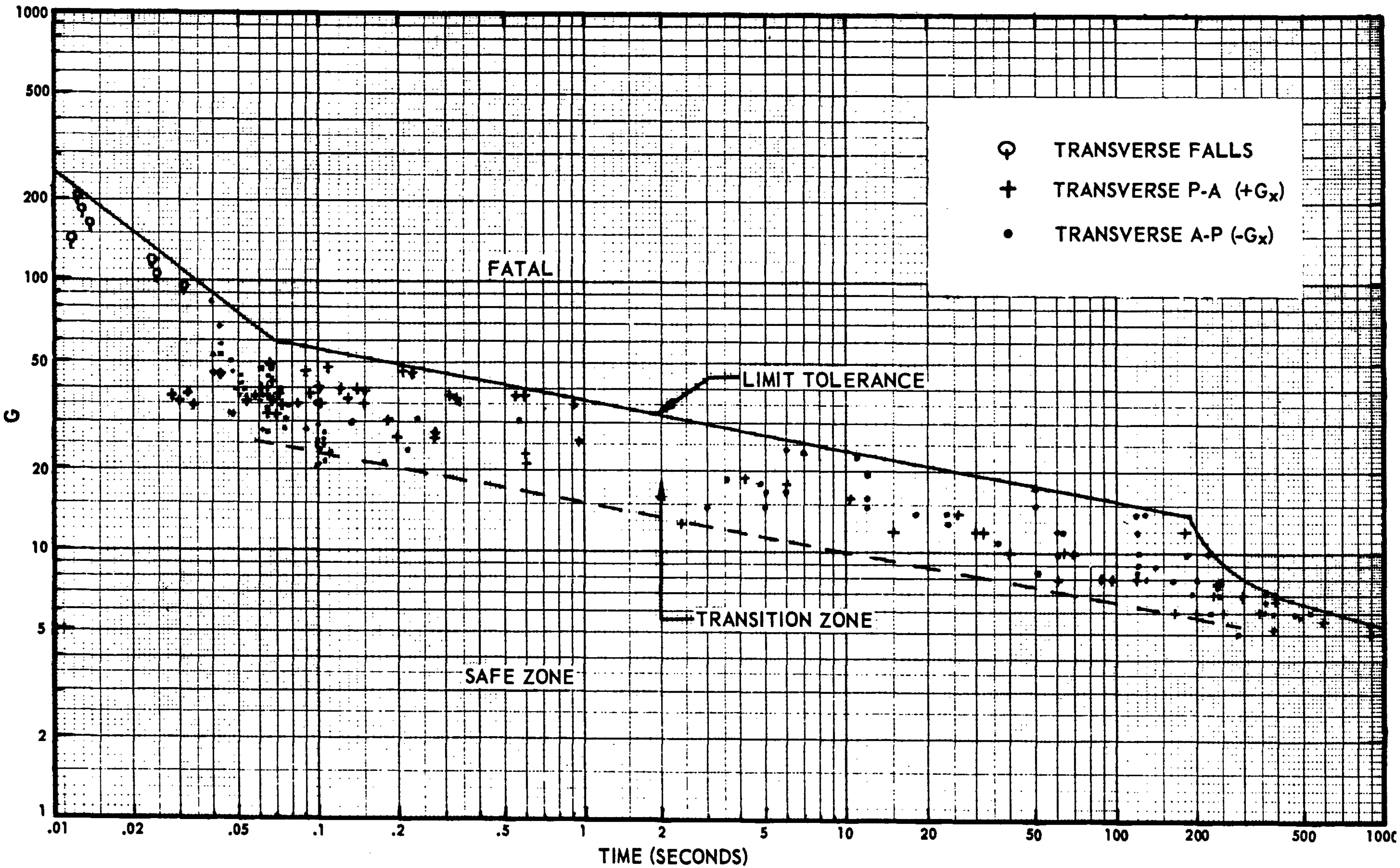
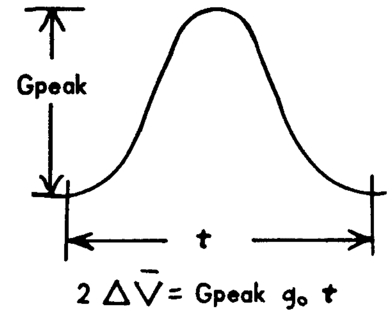


FIGURE 42 HUMAN TRANSVERSE ACCELERATION TOLERANCE—PEAK G VERSUS TIME



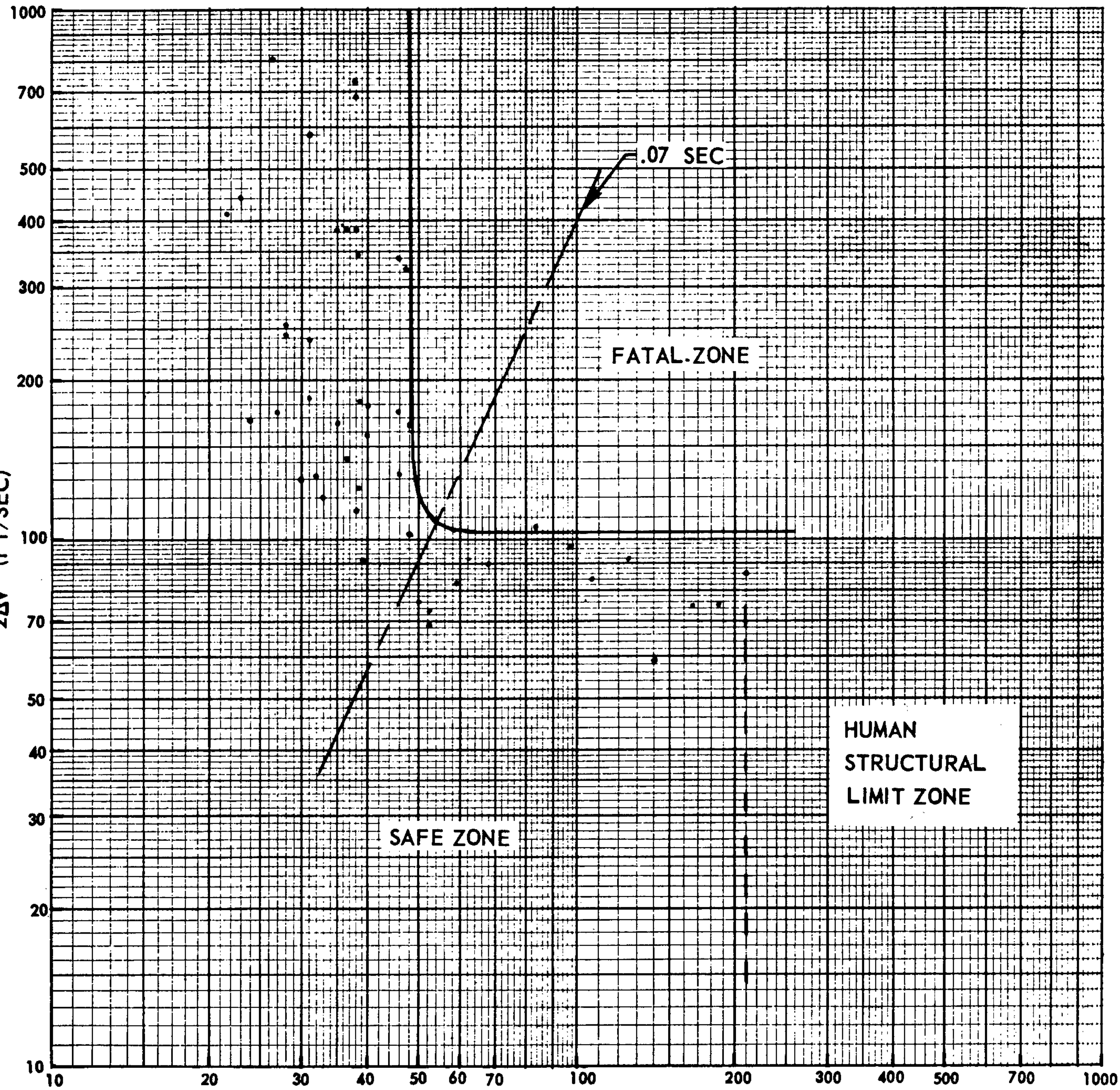


FIGURE 43 HUMAN TRANSVERSE IMPACT TOLERANCE — 2 DELTA $\bar{V}$ VS PEAK G

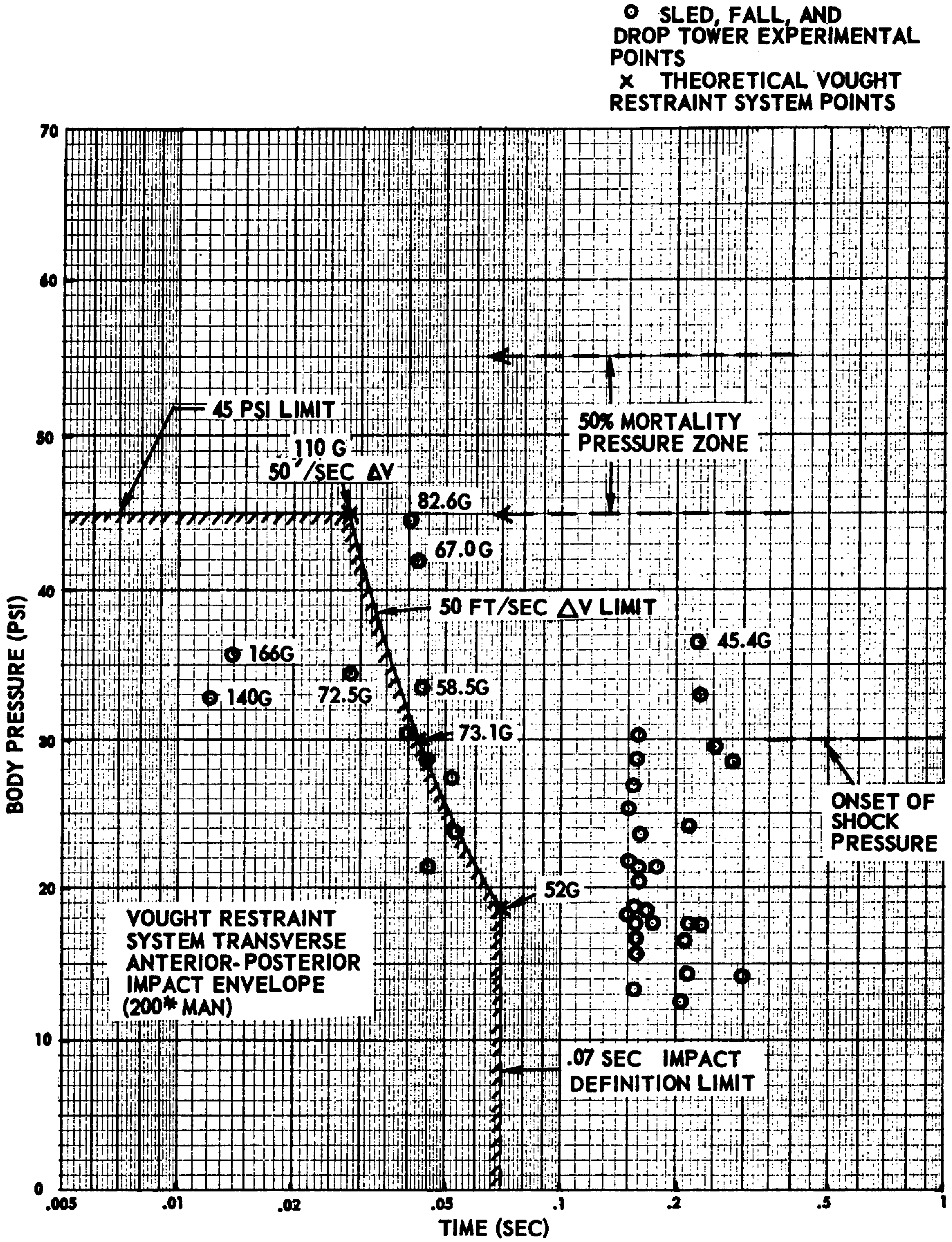


FIGURE 44 HUMAN TRANSVERSE IMPACT TOLERANCE ENVELOPES—DEFINED BY UNIT BODY PRESSURE, DELTA VELOCITY, AND TIME

APPENDIX II

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